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EFFECTIVENESS OF CAPPING IN ISOLATING CONTAMINATED DREDGED MATERIAL FROM BIOTA AND THE OVERLYING WATER

by

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The effectiveness of capping in chemically and biologically isolating contaminated dredged material was investigated using large- (250 ℓ) and small- (22.6 ℓ) scale laboratory reactor units. The ability of various cap materials to isolate contaminated dredged material was assessed in the large reactor units by following the movement of chemical contaminants and microbial spores contained in the capped dredged material into the overlying water column and

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by monitoring the biological uptake of chemical contaminants by clams and polychaetes. The depth of cap material needed to chemically isolate contaminated dredged material was assessed in the small-scale reactor units. Changes in overlying water concentrations of dissolved oxygen (DO), ammonium nitrogen (NH_4^+-N), manganese, and orthophosphate were monitored following isolation of the water column from air by placing a 4-cm layer of mineral oil on the surface. The constituents analyzed were selected due to their mobility under anaerobic conditions, ease of measurement, and generally high concentrations in contaminated dredged material compared to clean cap materials.

Three capping materials, sand, clay (New Haven Harbor sediment), and silt (Vicksburg silt), were evaluated for their efficiency in preventing transfer of contaminants from a contaminated sediment into the overlying water column and biota. In the presence of bioturbating polychaetes (*Nereis virens*) at densities of 100 large animals per square metre, a 50-cm cap of any of the three materials tested in the large chamber experiments was effective in preventing the transfer of chemical constituents and microbial spores to the overlying water and nonburrowing biota. Chemical analysis of polychaete tissue and visual observation showed that the polychaetes penetrated both the 5-cm and 50-cm caps of all materials tested.

A 5-cm cap in the presence of polychaetes was not completely effective in preventing the transfer of contaminants and microbial spores in the dredged material into the overlying water and biota. However, a 5-cm New Haven Harbor sediment or Vicksburg silt cap was relatively more effective than a 5-cm sand cap in preventing the movement of polychlorinated biphenyl or polyaromatic hydrocarbon compounds through the cap and into biota (clams). These bioaccumulation results were in relatively close agreement with results obtained in small reactor units for DO depletion and NH_4^+-N release. The efficiency of cap materials in preventing DO depletion and NH_4^+-N releases attributable to the capped dredged material was in the order: New Haven sediment > Vicksburg silt > sand. Cap materials with higher proportions of clay and silt should, therefore, be relatively more effective than cap materials consisting predominately of sand in preventing contaminant movement into the overlying water and biota. However, a thick cap (50 cm or more) of any of the materials tested effectively isolated the overlying water and nonburrowing biota from the contaminated sediment.

PREFACE

This study was conducted by the US Army Engineer Waterways Experiment Station (WES), Environmental Laboratory (EL), Vicksburg, Miss. Financial sponsorship was from the Long-Term Effects of Dredging Operations (LEDO) Program, which is sponsored by the Office, Chief of Engineers (OCE), US Army. LEDO is managed within EL's Environmental Effects of Dredging Programs, Dr. Robert M. Engler, Manager, and Mr. Robert L. Lazor, LEDO Coordinator. The Technical Monitors for OCE were Dr. Robert W. Pierce, Dr. William L. Klesch, and Mr. Charles W. Hummer.

Authors of this report were Drs. James M. Brannon and Douglas Gunnison, and Messrs. Ronald E. Hoeppel, Thomas C. Sturgis, and Issac Smith, Jr., all of the Aquatic Processes and Effects Group (APEG), EL. The study was conducted under the general supervision of Dr. Thomas L. Hart, Chief, APEG, and Mr. Donald L. Robey, Chief, Ecosystem Research and Simulation Division. The Chief of EL during this study was Dr. John Harrison.

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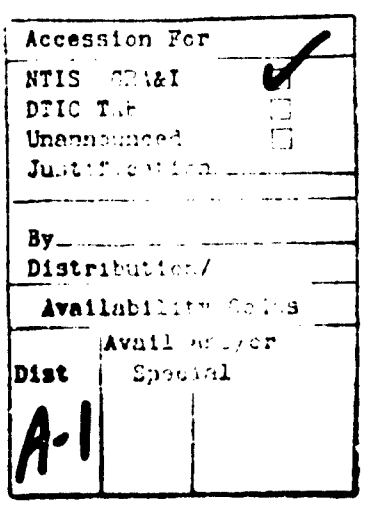

CONTENTS

	Page
PREFACE	1
PART I: INTRODUCTION	3
Background	3
Objectives	4
Approach	4
PART II: MATERIALS AND METHODS	5
Sediment Acquisition	5
Large Reactor Unit Experiments	5
Microbiological Studies	8
Small Reactor Unit Experiments	9
Analysis of Results	11
PART III: RESULTS	12
Sediment Chemical Characterization	12
Large Reactor Unit Experiments	12
Small Reactor Unit Experiments	19
PART IV: DISCUSSION	24
Cap Effectiveness	24
Thickness and Relative Effectiveness of Cap Material	26
PART V: SUMMARY AND CONCLUSIONS	28
REFERENCES	30
TABLES 1-18	
APPENDIX A: TISSUE AND WATER RESULTS	A1

EFFECTIVENESS OF CAPPING IN ISOLATING CONTAMINATED DREDGED MATERIAL FROM BIOTA AND THE OVERLYING WATER

PART I: INTRODUCTION

Background

1. Capping contaminated dredged material with uncontaminated dredged material to reduce the ecological impact of the contaminated material and rapidly render it harmless by physical means has been utilized by the New England Division and the New York District of the US Army Corps of Engineers in open-water disposal sites. These field studies have shown that capping is technically feasible and that the caps are stable under normal tidal and wave conditions (O'Conner and O'Conner 1983; Science Applications, Inc. (SAI) 1982). However, the efficacy of capping in isolating contaminants in dredged material from overlying water and from pelagic and benthic biota is unknown (O'Conner and O'Conner 1983). In the New York Bight, a mussel bioaccumulation study at the capping site indicated low body burdens that could have been due to bioconcentration of contaminants from ambient water as much as from the nearby sediments (O'Conner and O'Conner 1983). In Long Island Sound, mussels were also suspended in the water column at the sand- and silt-capped sites of the Stanford-Norwalk capping project. Concentrations of cobalt, copper, mercury, zinc, and vanadium fluctuated in the mussels over time, but these changes were thought to be unrelated to the caps because there was no increase in concentration in mussels at the capped site compared with mussels at control stations (Morton and Kemp 1980). Based on these and other field study results, bioaccumulation of contaminants by test organisms in the water column can result from sources other than dredged material (Kay 1984). Therefore, determining the ability of caps to isolate contaminated dredged material from the water column has proven to be a difficult question to answer in the field (Morton and Kemp 1980; O'Conner and O'Conner 1983).

2. When dredged material testing required under Public Law 922-532 (Ocean Dumping Act) reveals that the potential for ecological harm exists from disposal of dredged material, ocean disposal of that material may be prohibited. Capping contaminated dredged material with clean dredged material

following open-water disposal may be an alternative to other disposal methods, such as confined land disposal. For this option to exist on other than an experimental basis, the physical, chemical, biological, and microbial impacts and benefits of capping must be better understood. A prime concern is the efficiency of capping in isolating contaminated dredged material from the water column and from the biota, both pelagic and benthic.

Objectives

3. The objectives of this study were twofold:

   a. Determine relative effectiveness of different cap materials in isolating contaminated dredged sediments from organisms and the water column.

   b. Identify the minimum thickness of sand and fine-grained material that will inhibit sediment-water interactions between contaminated dredged sediment and the overlying water column.

Approach

4. The effectiveness of capping in chemically and biologically isolating contaminated dredged material from the overlying water column and biota was investigated using large- (250 ℓ) and small- (22.6 ℓ) scale laboratory reactor units. Initial analyses of the contaminated dredged material and three different cap materials demonstrated which chemical and microbial contaminants were most appropriate to monitor in the studies. The ability of various cap materials to isolate contaminated dredged material was then assessed by determining the movement of these contaminants into the overlying water column and the biota in the large reactor units. The depth of cap material needed to chemically isolate contaminated dredged material was evaluated in the small reactor units by following changes of dissolved oxygen and selected inorganic chemical species in the overlying water column.

PART II: MATERIALS AND METHODS

Sediment Acquisition

5. Contaminated and capping material samples were obtained from Black Rock and New Haven Harbors in Connecticut, respectively. These sites were selected because Black Rock sediments are highly contaminated while New Haven sediment was the first material used in the United States to cap contaminated material (O'Connor and O'Conner 1983). At each of ten locations within Black Rock Harbor, sediment in the navigation channel was obtained using a 0.1-m^2 gravity box corer to a depth of 1.21 m and placed in a 208-ℓ steel barrel. Five 208-ℓ barrels of New Haven Harbor sediment were obtained at 100-m intervals in the New Haven Reach using the box corer. Samples were then transported to the US Army Engineer Waterways Experiment Station (WES) within 3 days after collection. Upon arrival at WES, contents of the 10 barrels of Black Rock sediment and 5 barrels of New Haven sediment were separately composited and mixed, then returned to the barrels for storage at 4°C. Washed masonry sand was obtained locally as was Vicksburg silt for use as capping material.

Large Reactor Unit Experiments

6. Laboratory studies to assess the medium-term (40 days) effectiveness of various cap materials in isolating a contaminated sediment were conducted in a controlled environment chamber maintained at 20° ± 0.5°C, using modified 250-ℓ flow-through reactor units (Figure 1) described in detail by Gunnison et al. (1980). These chambers are 121 cm in height and measure 46 cm on a side. Modification included sealing of sampling ports with Plexiglas, removal of the mixing pump from the system, and provision for constant aeration of the water column. With the exception of the control units, to which only cap material was added, enough Black Rock sediment was added to result in a layer 17 cm deep on the bottom of each reactor unit. This sediment was then capped with either a thin (5 cm) or thick (50 cm) layer of cap material. Sixty litres of artificial seawater at 15°/oo, prepared from Tri S™ artificial sea salts, was then added as gently as possible to each reactor unit and allowed to equilibrate with aeration for 14 days. A 14-day equilibration time was

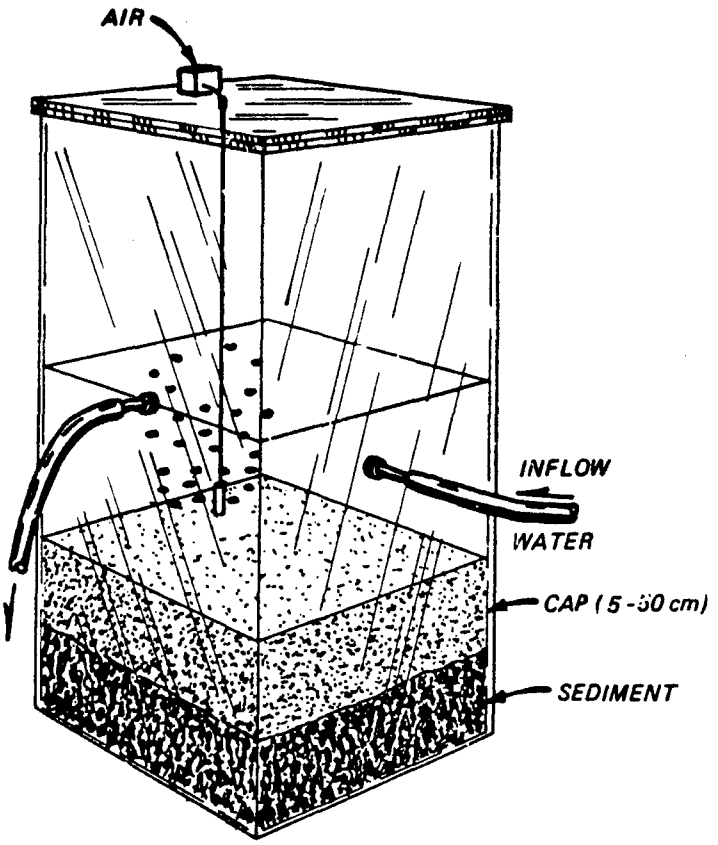

Figure 1. Large reactor units

selected to allow initial compaction to occur and material suspended during water addition to settle. At the end of the equilibration/consolidation period, flow-through of artificial seawater was initiated at a rate of 1.2 ℓ/hr. At this flow rate, 50 percent of the overlying water was replaced every 36 hr (Sprague 1969). The water column in each reactor unit was continuously aerated to ensure a well-mixed, aerobic water column.

7. Clams (*Rangia cuneata*) were used to determine if contaminants were moving through the cap and into the water column. Polychaetes (*Nereis virens*) were used to assess the effect of capping on contaminant bioaccumulation in infaunal organisms and to provide a source of bioturbation. Clams were obtained from Perdido Bay, Florida, and polychaetes from the Maine Bait Co., New Castle, Maine. Fresh batches of animals were obtained prior to the sand, New Haven Harbor, and Vicksburg silt capping experiments. All animals were acclimated to test conditions in the laboratory for at least 1 week prior to being added to the reactor units.

8. Clams and polychaetes were added to various units as shown in Table 1 following 4 days of flow-through operation in the reactor units. There were three replicates of each experimental treatment. Forty-two clams in a basket were suspended in the water column 5 cm above the sediment surface in each reactor unit. Twenty-one polychaetes ($100/m^2$) were added to each reactor unit designated to receive polychaetes. Concurrent with addition of clams and polychaetes to the reactor units, subsamples of these populations were removed from the holding tanks for initial tissue chemical characterization. Clams were immediately frozen, then divided into subsamples for polychlorinated biphenyls (PCB), polyaromatic hydrocarbons (PAH), and metals analysis; removed from their shells; and then placed in hexane-rinsed glass (PCB, PAH) or acid- (HCl) washed plastic (metals) containers and maintained frozen until analyzed. To remove sediment and food from their gut, polychaetes were first depurated for 24 hr in water identical to that in the reactor units. They were then divided into subsamples for PCB, PAH, and metals analysis, placed in appropriate glass (PCB, PAH) or plastic (metals) containers, and maintained frozen until analyzed. Polychaetes in each reactor unit were fed 2 g of ground TetraMin™ once each week during the experiment. Clams in each reactor unit were fed 6 g (wet weight) of green marine algae twice weekly. Algae were cultured according to methods described in US Environmental Protection Agency (USEPA) (1978). Twenty-one clams were removed from each reactor unit at 10- and 40-day intervals and handled in the same manner as described for initial clam samples. At the end of 40 days, polychaetes were removed from the sediment, depurated, and prepared for analysis in the same manner described for initial polychaete samples.

9. Water samples were obtained at the end of 40 days for subsequent chemical analyses. Samples to be used for PCB and PAH analyses were placed in 3.8-ℓ glass jars which had been hexane washed and dried at 105°C for 24 hr. Samples for metal analyses were filtered through 0.45-μm pore size membrane filters. The first 100 ml of filtrate was discarded. The subsequent filtrate was acidified to pH 1 with concentrated HNO_3. Water samples were analyzed for cadmium, copper, lead, and zinc using a Perkin-Elmer Model 2100 heated graphite atomizer and a Perkin-Elmer Model 503 atomic adsorption spectrophotometer. Mercury was determined using a Perkin-Elmer Model 503 atomic adsorption unit coupled to a Perkin-Elmer MHS-10 hydride generator. Unfiltered water samples were analyzed for total suspended solids using the method of Ballinger (1979).

10. Water, tissue, and sediment samples were analyzed for ten PCB isomer groups: total monochlorobiphenyls through total decachlorobiphenyls. Isomer group concentrations were determined following soxhlet extraction, H_2SO_4 cleanup, and quantification in an electron capture detector gas chromatograph. Eighteen compounds comprising the PAH family (Table 2) were also determined in water, sediment, and tissue samples. Samples were extracted overnight with a soxhlet using benzene:methanol. The aromatic hydrocarbon fraction was then separated using silica gel chromatography, concentrated, and subjected to capillary gas chromatographic analyses on a Hewlett Packard 5840A gas chromatograph equipped with a flame ionization detector. Individual compounds were quantified using analytical standards and an internal standard. Lipid concentrations were determined on each tissue sample (Food and Drug Administration (FDA) 1977). Tissue and sediment samples were analyzed for cadmium, copper, lead, zinc, and mercury using atomic absorption spectroscopy following appropriate sample digestion procedures (Ballinger 1979).

11. Total organic carbon (TOC) in sediment samples was determined by dry combustion (Allison 1965). Sediment particle-size distribution was determined using the method of Patrick (1958).

Microbiological Studies

Sediment analyses

12. Black Rock dredged material and capping materials were assayed for (a) total viable, aerobic, and heterotrophic bacteria; (b) total coliform (TC) bacteria; (c) fecal coliform (FC) bacteria; (d) *Salmonella* spp. (Salmonellae); and (e) *Clostridium perfringens* prior to loading of the chambers. Identification of isolates from the fecal coliform and salmonella assays was performed by biochemical testing as described below.

13. Total heterotrophic bacteria were enumerated by the pour plate method on Standard Methods agar (BBL Microbiology Systems, Cockeysville, Md.) incubated at 25°C for 72 hr. The TC and FC bacteria concentrations were determined by the five-tube most probable number (MPN) method using lauryl sulfate tryptose broth for the presumptive tests. Confirmations for TC and FC were conducted with brilliant green lactose bile broth incubated at 35 ± 1°C and EC broth incubated at 45° ± 0.5°C, respectively, as described in Standard

Methods (American Public Health Association 1980). Sediment concentrations of salmonellae were assessed by the five-tube MPN method using selenite cystine and tetrathionate broths for enrichment, brilliant green and bismuth sulfite agar plates for isolation, and triple sugar iron (TSI) agar slants for primary biochemical screening (FDA 1978). All potentially positive isolates from EC broth (FC testing) and TSI slants (salmonellae) were identified using API020E biochemical test strips (Analytab Products, Division of Ayerst Labs, Plainview, N.Y.). *Clostridium perfringens* was enumerated in the sediment by the membrane filter (mCP) method of Bisson and Cabelli (1979) using the shake, sonication, and settling procedures previously developed and evaluated for marine sediment (Emerson and Cabelli 1982; Emerson 1982). Representative wet weight sediment aliquots were diluted serially with 0.01 M phosphate-buffered saline for all assays except the mCP. A 0.1-percent peptone water diluent was used in the mCP testing using the supernatant from each sediment suspension, following a 10-min settling period, as the initial dilution.

Water analyses

14. Water samples from each previously described large reactor unit were also monitored for viable *Clostridium perfringens* spore densities using the mCP method of Bisson and Cabelli (1979). One-tenth percent peptone water was used as the buffer solution, and incubation of mCP plates was at 44° ± 0.5°C for 18 to 20 hr. Water samples were assayed 2 hr before adding clams and polychaetes, and 6, 15, 28, 37, and 41 days after addition of these organisms.

Small Reactor Unit Experiments

15. The ability of capping material to chemically seal contaminated dredged sediment containing relatively mobile and oxygen-demanding constituents from the overlying water was determined in 22.6-ℓ, cylindrical, Plexiglas leaching columns (Figure 2). The design and sediment loading arrangement of an individual column is shown in Figure 2. Sand, silt, and clay capping materials were evaluated; caps of these materials ranging from 2 to 28 cm in depth were used. These experiments were conducted in a controlled environment chamber where the temperature was regulated at 20° ± 0.5°C.

16. The overlying water (15-percent salinity) in all small columns was aerated for 3 days by slowly bubbling air through the water. This ensured

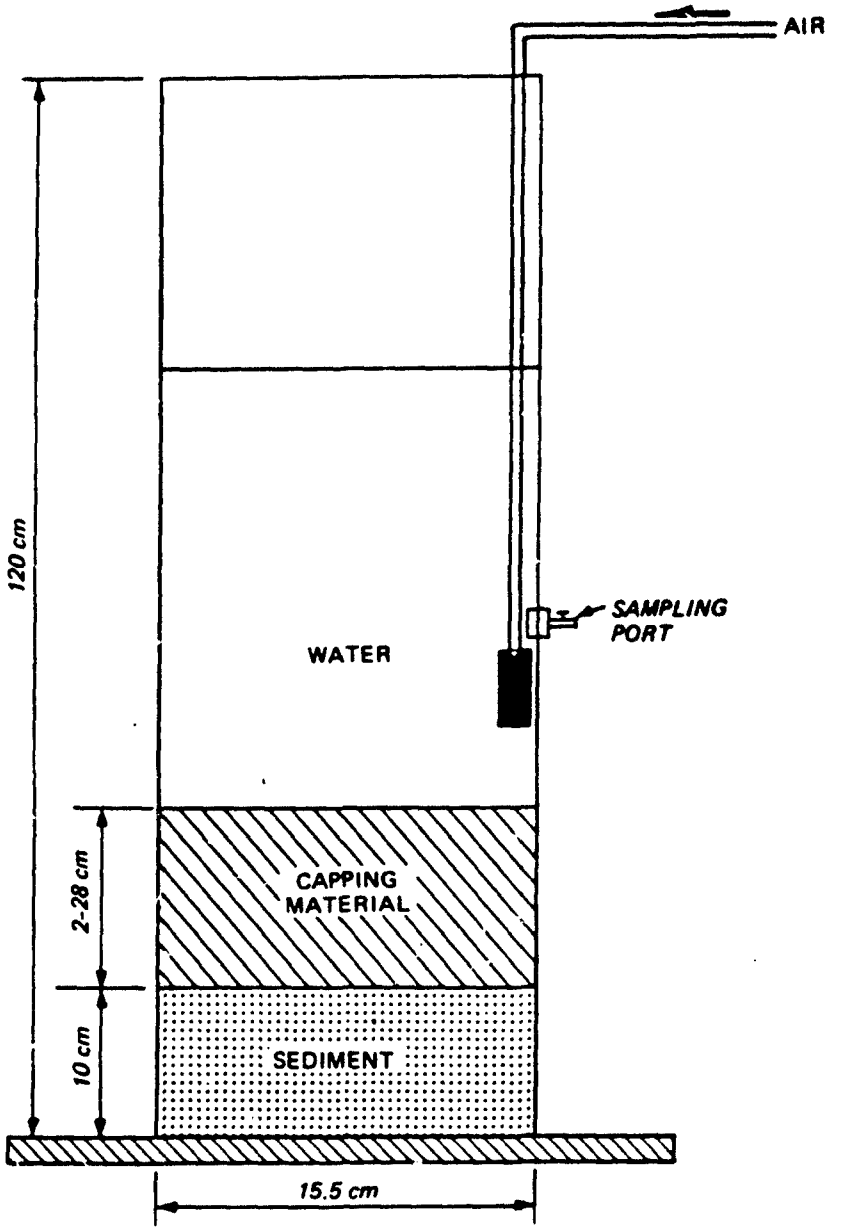

Figure 2. Small rector units

that dissolved oxygen (DO) concentration for all units was relatively uniform (±0.5 mg/ℓ) at the start of the experiment. At the end of 3 days, the aeration apparatus was removed and a layer of mineral oil (4 cm) added to seal the surface of the water column from the atmosphere. Water samples were taken initially and at regular intervals for 21 days or until the measured DO concentration was depleted. The overlying water was manually mixed daily without disturbing the sediment with a Plexiglas stirring plunger that was suspended

between the sediment and the mineral oil layer. Stirring was conducted to prevent establishment of concentration gradients in the water column and to ensure a well-mixed water column. All experiments were conducted in triplicate.

17. Dissolved oxygen was measured in samples collected by permitting water to flow gently from a tube attached to the reactor unit sampling port into a standard biochemical oxygen demand (BOD) bottle. Dissolved oxygen was determined with the azide modification of the Winkler method as described in Standard Methods (APHA 1980).

18. Samples to be analyzed for ammonium nitrogen, orthophosphate, and manganese, relatively mobile compounds that are released under anaerobic conditions, were cleared of particulate matter by passage through a 0.45-μm membrane filter under a nitrogen atmosphere. Manganese samples were preserved by acidification to pH 1 with concentrated HCl. Manganese concentrations were determined using direct flame aspiration with a Perkin-Elmer Model 306 atomic absorption spectrophotometer. Samples for ammonium nitrogen and orthophosphate analyses were preserved by acidification with concentrated HCl to pH 2 and immediate freezing and storage at -4°C. Ammonium nitrogen and orthophosphate concentrations were determined using a Technicon Autoanalyzer II, in accordance with recommended procedures (Ballinger 1979).

Analysis of Results

19. Means and standard errors were determined for each parameter within a treatment. To determine the statistical significance of differences between means, t-tests were conducted. Statements of significance made in the text refer to the 5-percent level ($p < 0.05$) or less.

PART III: RESULTS

Sediment Chemical Characterization

20. Sediment from Black Rock had a higher concentration of heavy metals than the three capping materials (Table 3). For example, copper concentrations in Black Rock sediment exceeded those in the three capping materials by at least an order of magnitude. Black Rock sediments were also higher in total organic carbon (TOC), containing 8.2 percent carbon compared to 3.1 percent TOC in the New Haven sediment, which had the highest level of this constituent among the capping materials. As also shown in Table 3, the cap materials ranged from 100 percent sand to material consisting of over 80 percent silt.

21. Black Rock sediments contained much higher levels of PAH compounds than did any of the cap materials (Table 4). PAH compounds were not detected in the sand and Vicksburg silt cap materials. Only the New Haven cap materials contained detectable levels of PAH.

22. Sediment from Black Rock was more contaminated with PCBs than any of the cap materials (Table 5). Total PCB concentration in Black Rock sediment was 17.63 µg/g dry weight compared to 1.02 µg/g dry weight in New Haven cap material, which was next highest in PCB concentration. Total hexachlorobiphenyl constituted the largest fraction (40.3 percent) of PCB in Black Rock sediments. In contrast, total dichlorobiphenyls comprised the largest fraction (71.6 percent) of PCB in the New Haven cap material.

Large Reactor Unit Experiments

Contaminant release and uptake

23. Concentration values for selected contaminants were determined in the water column and in clams and polychaetes to assess the ability of 5 and 50 cm of cap material to isolate a contaminated dredged material. The clams and polychaetes did not suffer excessive mortality in the reactor units; 95 percent or more of the animals added initially to the experimental units survived in good condition until sampled and used for tissue analyses.

24. Water column. Heavy metal (Table 6) and PCB isomer group concentrations (Table 7) in the water column above capped sediments did not generally differ from their respective concentrations in control (sand, New Haven,

and silt) unit water columns. Some water samples were lost during shipping, but this did not seriously impact upon the analyses of results. Water column metals data are unavailable for the Vicksburg silt cap treatment because of sample loss during shipping. Inflow water concentrations were measured on single samples taken concurrently with other water samples and therefore have no associated error term. Total trichlorobiphenyls (Isomer Group No. 3 in Table 7), however, were statistically higher ($p < 0.05$) in water overlying sediment capped with 50 cm of sand and could possibly be higher in the 5-cm cap units (Table 7), although the single surviving 5-cm water sample did not allow statistical comparison. Water column data for PCBs in the sand cap experiment are incomplete due to sample container breakage during shipping. Examination of the PCB concentrations in the inflow water (Table 7) reveals that PCB concentrations varied somewhat during the course of the experiment. Most marked changes were confined, however, to PCB compounds containing from one to four chlorine atoms.

25. Replicate samples for PAHs in the water column were composited to obtain lower detection limits by increasing the volume of water available for extraction for use in the analyses. Even using these techniques, which gave detection limits of 1 ng/ℓ, water column PAH concentrations were very low. Data for water column PAH concentrations in the New Haven and Vicksburg silt treatments are summarized in Table 8. Because of the low concentrations encountered, only data for total PAHs are given. Data for the sand cap experiments were below detection limits (1 ng/ℓ). However, many of the samples were broken during shipping, and this prevented compositing of the full 13.2 ℓ of water for each treatment. There was no apparent enhancement of water column PAH concentrations compared to controls in any of the treatments, including uncapped Black Rock sediment.

26. Clams. All tissue concentrations of PCB and PAH have been normalized to organism lipid concentration. This was necessary since organisms obtained at differing times during the year can exhibit wide variations in lipid concentration. Lipid concentration can significantly affect the bioaccumulation of hydrophobic organic compounds in organisms (Schneider 1982; Stout 1980; Geyer et al. 1982). Lipid-normalized concentrations can be converted to a whole body basis by dividing the lipid normalized concentration by 100, then multiplying by percent lipids. Average percent lipids for each treatment, cap material, and organism can be found in Appendix Table A1.

Heavy metal, PCB, and PAH concentrations determined in organisms prior to exposure (time zero) are presented in Table A2.

27. Heavy metals. Heavy metal concentration in *Rangia* tissue did not significantly exceed that of *Rangia* exposed to the cap material alone (controls) in any of the treatments following 10 days of exposure (Table 9). *Rangia* copper concentration in the 5-cm + polychaete treatment of the Vicksburg silt cap experiment was significantly higher than copper concentrations in *Rangia* exposed only to Vicksburg silt (Table 10) for 40 days. There was no significant difference, however, between copper concentrations in *Rangia* exposed to Vicksburg silt and Black Rock sediment. This statistical ($p < 0.05$) difference may therefore have been due to chance or to differences between the *Rangia*.

28. Comparison of organism metal concentrations between cap materials is complicated by differing heavy metal concentrations in the *Rangia* prior to exposure (Table A2). Each experiment (sand cap, New Haven cap, Vicksburg silt cap) was conducted using *Rangia* collected expressly for that experiment. Lead concentrations in *Rangia*, for example, were generally higher in sand cap experiments compared to New Haven and Vicksburg silt cap experiments following 10 days of exposure (Table 9). Examination of sand cap time zero metal concentrations (Table A2), however, revealed that lead concentrations in *Rangia* were initially much higher in this group of organisms compared to those obtained for the New Haven and Vicksburg silt experiments. *Rangia* mercury concentrations showed trends opposite to those of lead (Table A2).

29. PAH. *Rangia* PAH concentrations in the 5-cm + polychaete treatment for each cap experiment generally exceeded concentrations found in their respective cap material controls following 10 days of exposure (Table 11). This pattern was generally repeated in results of the 40-day exposure (Table 12), although variability in the 5-cm + polychaete treatment during the sand cap experiment precluded statistical conclusions at the 5-percent ($p < 0.05$) level. Concentrations of PAH in the 5-cm + polychaete treatment were, however, substantially higher than controls. No treatment other than the 5-cm + polychaete significantly ($p < 0.05$) exceeded control values in any of the cap materials.

30. To assess the relative efficiency of different type cap materials in the 5-cm + polychaete treatment, control PAH values were subtracted from 5-cm + polychaete treatment PAH values for *Rangia* in each cap experiment

following 40 days of exposure. Forty days of exposure should have allowed initial differences in *Rangia* PAH concentrations to have equalized. Values derived in this manner were 128, 33, and 41 µg PAH/g lipid for the sand cap, New Haven cap, and Vicksburg silt cap experiments, respectively. Based on these results, the efficiency of the cap material in preventing contaminant transfer to biota in the presence of bioturbation increased in the order New Haven cap > Vicksburg silt cap > sand cap.

31. PCB. *Rangia* PCB concentrations generally exceeded that of the *Rangia* exposed to the cap material (controls) in the 5-cm + polychaete treatment for all cap materials (Table 13) following 10 days of exposure. Additionally, *Rangia* PCB concentrations in the 5-cm cap without polychaetes treatment significantly exceeded that of cap material controls for PCB isomer groups containing six and five chlorine atoms in the sand cap and New Haven cap experiments, respectively (Table 13). Concentrations of PCBs in *Rangia* tissue significantly ($p < 0.05$) exceeded that of cap material controls only in the 5-cm + polychaete treatment for all cap materials following 40 days of exposure (Table 14).

32. It appeared that the New Haven and Vicksburg silt caps were more effective than a sand cap in preventing PCB uptake by *Rangia* in the 5-cm + polychaete treatment. Subtracting cap material control PCB concentrations from PCB values in the 5-cm + polychaete treatment following 40 days of exposure gave values of 79.7, 49.0, and 42.3 µg total PCB/g lipid for the sand cap, New Haven cap, and Vicksburg silt cap, respectively. Under these bioturbation conditions, cap efficiency increased in the order Vicksburg silt cap $\geq$ New Haven cap > sand cap.

33. Polychaetes. Significant copper bioaccumulation by polychaetes (*Nereis virens*) compared to controls was noted in the 5-cm + polychaete treatment during the sand and Vicksburg silt experiments (Table 15), but not in the New Haven experiment. Polychaetes also accumulated significantly higher cadmium concentrations than controls in both the 5-cm and 50-cm sand cap + polychaetes treatments.

34. Concentrations of PAH in *Nereis* in the 5-cm + polychaete treatments of all cap materials were generally substantially higher than cap material control animals (Table 16). However, only in the Vicksburg silt cap were *Nereis* PAH concentrations in the 5-cm + polychaete treatment significantly ($p < 0.05$) higher than values in cap material controls. High variability

among replicate *Nereis* samples did not permit statistical conclusions in the sand and New Haven experiments at the 5-percent ($p < 0.05$) level.

35. Concentrations of PCBs in *Nereis* were significantly ($p < 0.05$) higher in the 5-cm + polychaete treatment compared to controls for total PCB and two PCB isomer groups (Table 17) in the Vicksburg silt cap experiment. In the other experiments, significant differences from controls were seen for total hexachlorobiphenyls (6 Cl) in the 5-cm + polychaete treatment of the sand and New Haven cap experiment and for total heptachlorobiphenyls (7 Cl) in the 5- and 50-cm + polychaete treatments of the New Haven experiment. Contaminant concentrations in *Nereis* at time zero are given in Table A3.

Microbial releases

36. Black Rock sediment assays. Total viable aerobic, heterotrophic bacteria in the Black Rock sediment averaged 105,000 per gram wet weight sediment (305,000/g dry weight sediment). These numbers are one to three orders of magnitude lower than in oxidized sediments (Alexander 1977), but were not unexpected for a highly reduced, contaminated sediment. The spread plate method usually gives slightly higher colony counts than the pour plate method (Young 1978); however, many of the spread plates displayed spreading surface growth of numerous motile bacteria, which masked some small colonies on most plates.

37. The TC and FC MPN assays indicated low viable levels of fecal contamination indicator bacteria. Estimated TC and FC numbers were similar, with average values of less than four (maximum of 20) per 10 g wet sediment (average of 1/g dry sediment). These low concentrations, especially for FC, are typical for highly reduced, contaminated subsurface marine sediments (Attwell and Colwell 1981). A previous study of indicator bacteria in core samples from Long Island Sound and adjacent harbor areas indicated that TC and FC bacteria are seldom found at elevated numbers below the uppermost layer of fine-grained, fecal-contaminated marine sediments (Babinchak et al. 1977). Biochemical testing showed that the single FC isolate obtained from 1 g of Black Rock sediment was *Escherichia coli*, a typical FC bacterium.

38. Assays for *Salmonella* species and other pathogenic members of the salmonellae all proved negative. The MPN tables thus indicated numbers of less than two viable cells per gram wet sediment. The median ratio of salmonellae to FC in freshwater muds is about 1:14,000 (Van Donsel and Geldreich 1971), and the die-off of both is more rapid in marine versus freshwater

environments (Mitchell 1968). Biochemical testing of isolates indicated that none were even closely related to the salmonellae group. The isolates could not be specifically identified, but most proved to be pseudomonad bacteria that utilized the high ambient concentrations of petroleum residues in the Black Rock sediment.

39. The *Clostridium perfringens* membrane filter (mCP) assays of six replicate Black Rock Harbor sediment samples showed very high levels of cells and/or spores. The mCP tests, which incorporate a highly selective growth medium for this bacterial species, gave an average enumeration of 214,000 per gram wet sediment (628,000/g dry weight sediment). A less selective medium, SPS agar (BBL Microbiology Systems Cockeysville, Md.), was also used for comparative purposes. SPS agar pour plate results gave average counts of 355,000 per gram wet sediment (1.03×10^6/g dry weight sediment). Evaluations of the sonicate-settling and shake-settling procedures outlined for mCP sediment assays (Emerson 1982) showed that sonication for 10 sec at moderate energies (i.e., 100-200 W at the probe) gave the highest mCP counts.

40. Cap material assays. *Clostridium perfringens* was also enumerated in the three materials used to cap Black Rock sediment. Each sediment was assayed by the mCP procedure in triplicate.

41. The washed sand and Vicksburg silt capping materials each contained less than 10 *C. perfringens* per gram dry sediment. The sediment from New Haven showed relatively low densities of *C. perfringens* in comparison to Black Rock sediment; wet and dry weight enumerations were 8,700 and 30,000 per gram, respectively. The low numbers or absence of *C. perfringens* in the three cap materials, compared to the very high densities in the underlying Black Rock Harbor sediment, made monitoring of *C. perfringens* spores in the overlying test chamber water column a very useful indicator of spore or particulate movement through each cap material.

42. Following 40 days of water column monitoring of chambers containing Black Rock sediment capped with Vicksburg silt, four cores 65 mm in diameter were taken in four test chambers containing 50-cm caps. Two chambers contained no polychaete worms while the other two chambers contained polychaetes. Data for three core segments from each core are summarized in Figure 3. All samples from chambers without polychaetes lacked detectable numbers of *C. perfringens* (< 5/g dry weight) whereas low but highly variable numbers were found in all three horizons in cores from chambers with polychaetes. Visual

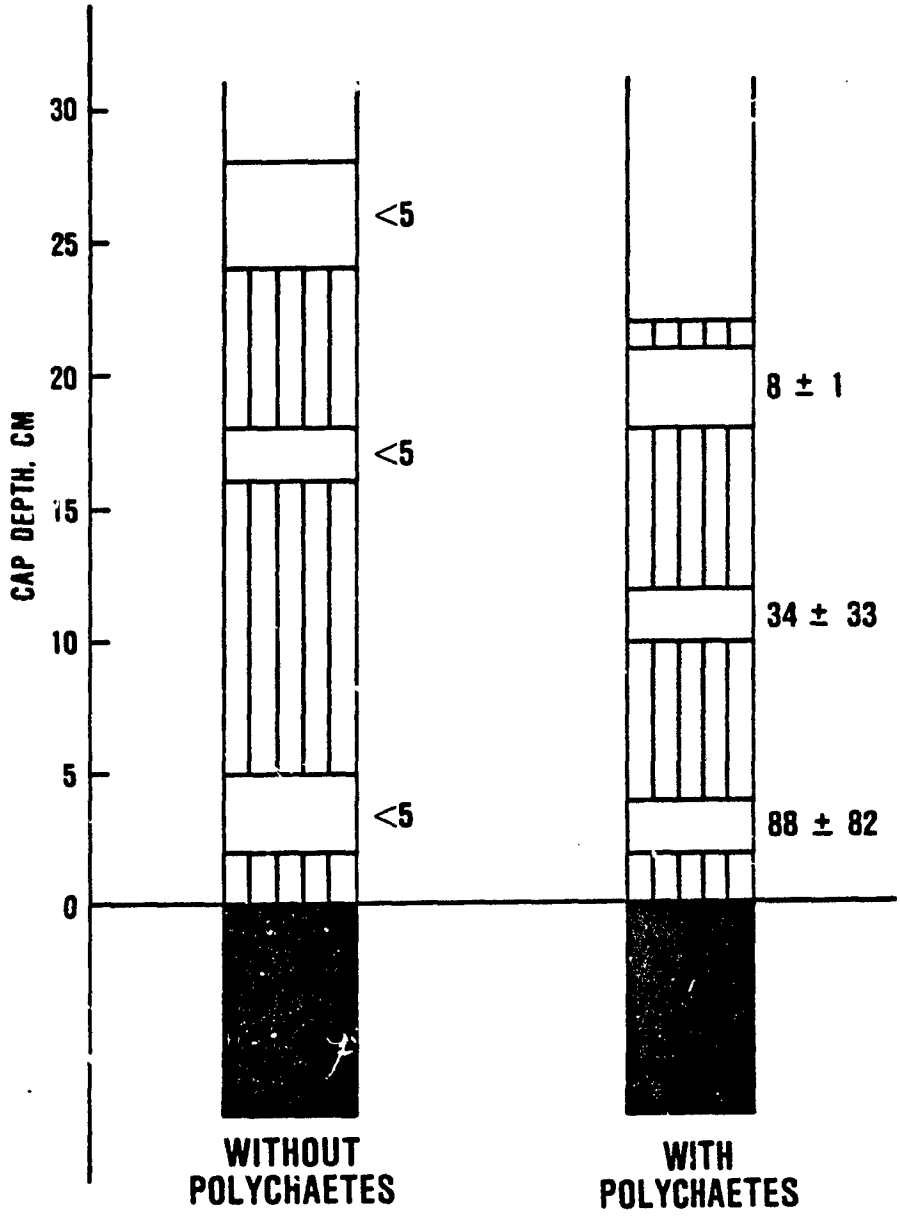

Figure 3. Enumeration of *C. perfringens* in core samples taken from chambers with and without polychaetes and having 50-cm Vicksburg silt caps (No./g dry sediment ± standard error)

observation showed that the polychaetes repeatedly penetrated 50 cm of all cap materials.

43. Water column assays. *Clostridium perfringens*, which occurs in very high numbers in the Black Rock sediment, is a fecal pollution indicator and pathogenic bacterium as well as a strict anaerobe, i.e., does not grow in an aerated water column (Bisson and Cabelli 1980). Absence of vegetative growth of *C. perfringens* in the water column was verified by heating previously enumerated water samples at 60°C for 18 min. This temperature kills vegetative cells while sparing most of the heat-resistant endospores (Bisson and Cabelli 1979). Comparisons of initial and heat-treated water samples gave statistically ($p < 0.05$) similar results, thus strongly indicating the absence of vegetative growth in the aerated water column. Therefore, monitoring of viable *C. perfringens* spore densities in the aerated water column of the test chambers could serve to evaluate the movement of very small discrete particles through the various caps covering the Black Rock Harbor sediment. Endospores of clostridia are less than 1 μ in diameter, smaller than most bacteria and very fine clay-sized particles, and do not germinate and grow at temperatures less than 20°C (Granberg 1983).

44. Spore counts of *C. perfringens* in the water column of treatments containing only Black Rock Harbor sediments greatly exceeded spore counts in waters overlying any of the cap materials (Table 18). Spores of *C. perfringens* were not detected in the inflow water. Regardless of the type of cap material, elevated spore counts of *C. perfringens* relative to cap material controls were observed in treatments containing a 5-cm cap + polychaetes. Despite visual and chemical confirmation that polychaetes breached the 50-cm caps, water column spore data from this treatment (50-cm cap + polychaetes) were comparable to their respective controls.

Small Reactor Unit Experiments

Water column oxygen depletion

45. Small column experiments were conducted to determine the depth of cap necessary to chemically isolate Black Rock sediment from the water column. Dissolved oxygen depletion in the water column would not normally be expected to be a problem in an open water environment because of mixing and reaeration. Dissolved oxygen depletion, however, does serve as a tracer for determining

how effectively a cap can isolate the underlying dredged material, such as Black Rock material, that possesses a high oxygen demand.

46. The effect of cap depth on DO depletion rates in the water overlying various types and depths of cap material is summarized in Figure 4. Oxygen depletion rates were derived by performing linear regression analyses of mass uptake or release per unit area (milligrams per square metre) versus time. Rates plotted are the mean of three replicates and represent values greater than baseline (i.e. oxygen demand of cap alone). Complete results on oxygen demand are presented in Appendix Table A4. Results showed that a 2-cm cap of New Haven sediment resulted in complete inhibition of oxygen demand above that of the New Haven cap material itself (i.e. oxygen demand attributable to Black Rock sediment was masked by the high oxygen demand from the New Haven cap), while 2 cm of Vicksburg silt and the sand caps resulted in 81- and 40-percent reductions in oxygen demand rates, respectively. In the oxygen demand rate curve for diluted Black Rock sediment capped with sand there was little reduction in oxygen demand with even a 14-cm sand cap. Diluted Black Rock sediment was produced by adding deoxygenated water to Black Rock sediment until the solids content had been reduced to 30 percent from the original 54 percent. This diluted sediment would be more representative of hydraulically dredged sediment than clamshell dredged sediment and was observed to undergo very irregular compaction when cap materials were added to the surface.

47. The cap depths required to isolate the overlying water column from oxygen demand due to Black Rock sediment was 2 cm for New Haven, 18 cm for Vicksburg silt, and 22 cm for a sand cap. Sand caps up to 30 cm deep were unable to totally isolate oxygen demand attributable to the diluted Black Rock sediment from the water column.

Ammonium-nitrogen releases

48. Ammonium-nitrogen (NH_4^+-N) release rates to the overlying water, derived in the same manner as oxygen depletion rates, are presented as a function of the type and depth of cap material used in Figure 5. Complete data are presented in Appendix Table A5. Results showed that a 2-cm depth of all cap materials substantially reduced (42 percent to 61 percent) releases of NH_4^+-N to the overlying water. There was no significant ($p < 0.05$) release of NH_4^+-N greater than that of the cap material alone when a cap depth of 22 cm of

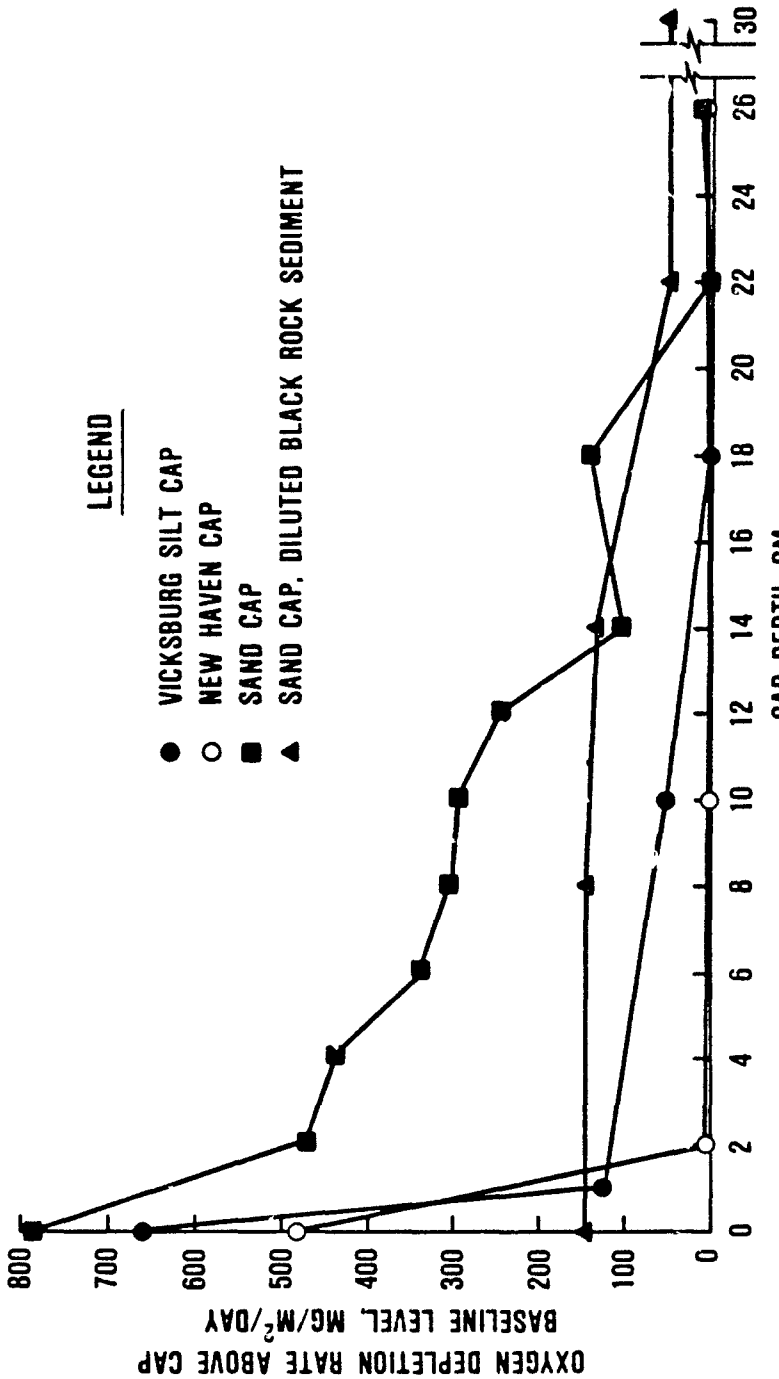

Figure 4. Effect of cap depth on overlying water oxygen demand

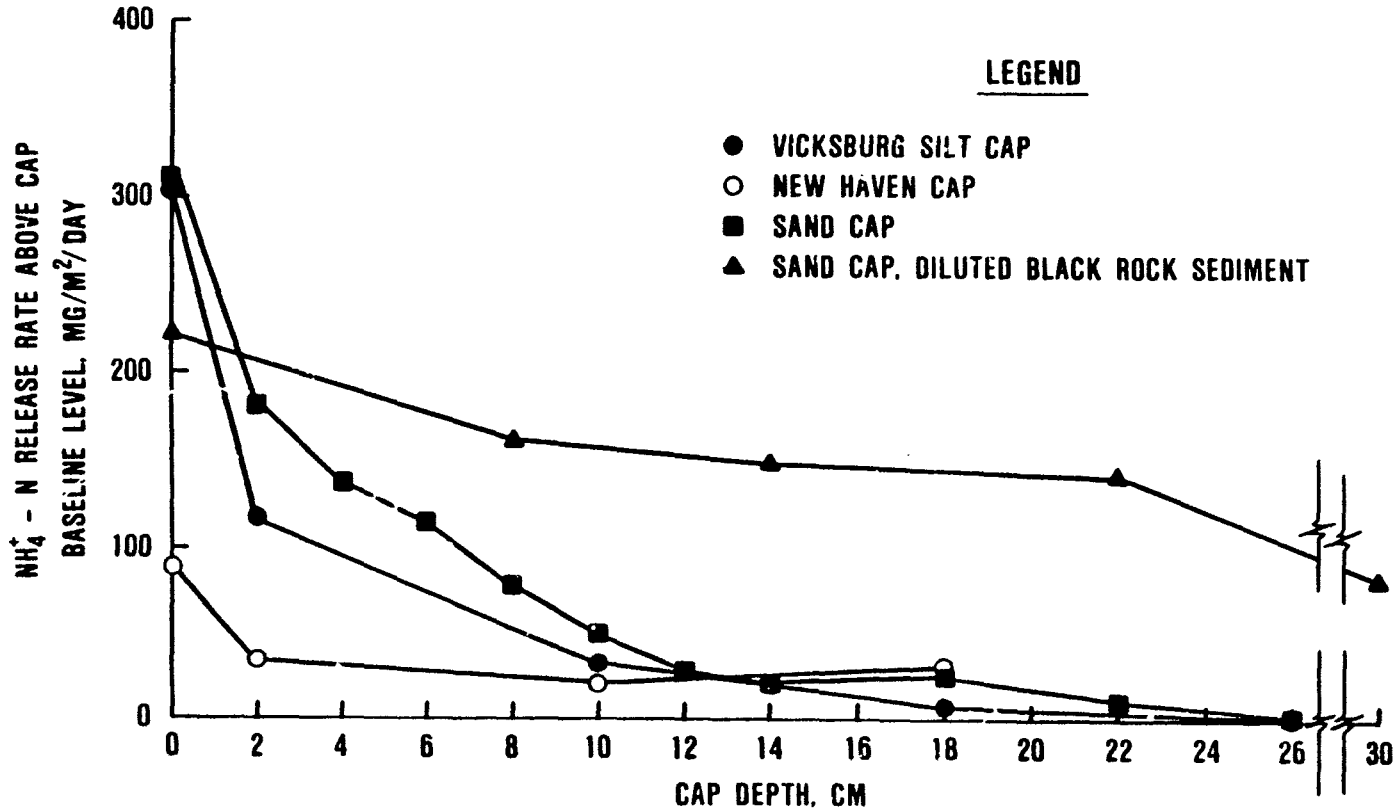

Figure 5. Effect of cap depth on NH_4^+-N release rates

sand, 18 cm of Vicksburg silt, and 10 cm of New Haven sediment was reached. Capping of diluted Black Rock sediment with sand required a cap depth of 30 cm to obtain a 63-percent reduction in NH_4^+-N release rate.

Manganese and orthophosphate releases

49. Determination of cap depths necessary to chemically seal a dredged sediment was also attempted using manganese and orthophosphate releases as tracers. These parameters proved unsuitable because releases from cap materials generally exceeded or closely approximated those measured in Black Rock sediments. Use of these parameters as tracers was therefore not pursued.

PART IV: DISCUSSION

50. Results of this study have demonstrated that capping can isolate contaminated dredged material from the water column and nonburrowing aquatic organisms. This conclusion is based on analysis of water, tissue, and microbial data.

51. There was a large amount of variability associated with both the microbial and bioaccumulation data. This is similar to the bioaccumulation variability observed in the data of Rubinstein, Lores, and Gregory (1983) from aquaria containing *Nereis virens*, *Mercenaria mercenaria*, and *Palaemonetes pugio*. It is highly probable that much of the variability observed represents differences in exposure conditions caused by polychaete activity among chambers. For example, the high variability in numbers of *C. perfringens* for Vicksburg silt core horizons containing polychaetes (e.g., 88 ± 82/g dry sediment at 2 cm above the cap/Black Rock sediment interface) suggests that distinct burrows were formed by the worms and that most movement of particulate contaminants through the bioturbated caps was through these burrow systems. Also, spore counts of *C. perfringens* in the overlying water showed that cap breaching within a treatment did not necessarily occur at the same time, but was somewhat staggered over time.

Cap Effectiveness

52. Clam tissue analyses, water column chemical data, and microbial results clearly showed that a 50-cm cap of sand, silt, or New Haven sediment served as an effective barrier to movement of contaminants from dredged material. This 50-cm depth of cap material was effective in preventing the movement of contaminants into the water column and nonburrowing organisms despite the presence of the large (300 mm or larger) polychaete *N. virens*. Visual observations during retrieval for analyses revealed that the polychaetes had burrowed into the Black Rock sediment through both the 5-cm and 50-cm caps. Cap breaching by the polychaetes offers contaminants in the Black Rock sediment an easier path into the overlying water than if the cap remained unbreached. In some instances, contaminant concentrations in polychaetes in treatments with a 50-cm cap were significantly higher than controls, but this was not generally the case. It is postulated that the polychaetes were able

to regulate their exposure to the contaminated dredged material by moving up and down in the cap. In the 5-cm cap + polychaete treatments, increased incidences of significant contaminant bioaccumulation by *Nereis* compared with that in the 50-cm cap + polychaete treatment may have been due to the inability of *Nereis* to avoid contaminated sediment when residing in the shallower cap.

53. It is important to emphasize that the bioturbation in this study may have been more severe than normally encountered in the field. Rhoads, McCall, and Yingst (1978) reported that polychaetes observed recolonizing a dredged material disposal site in Long Island Sound were *Streblospio benedicti*, *Capitella capitata*, and *Nephtys incisa*. Of these polychaete species, *Nephtys*, at 50 mm, was the longest measured. For *Nephtys*, an increase in worm size has been shown to produce a corresponding increase in burrow length and depth (Davis and Miller 1979; Davis 1980). The data of Davis (1980) showed that the largest 1- to 2-year-old *Nephtys* (0.6 g wet weight) burrowed to a depth of approximately 8 cm. The *N. virens* used in this study are among the largest of the polychaete species and often measure up to 450 mm in length (Arnold 1968). The *Nereis* used in this study were generally 300 mm or longer, weighed from 3 to 4 g wet weight, and burrowed to much greater depths (at least 50 cm) than do smaller polychaete species. Bioturbation was therefore much greater than would be expected of the polychaete assemblage in an ocean disposal site. Bioturbation depth at a field site must be determined prior to capping operations so that the contaminated dredged material can be isolated from all burrowing organisms.

54. The impacts of bioturbation on cap materials were well illustrated by spore enumeration data conducted in cores taken from 50-cm Vicksburg silt cap treatments (Figure 3). In the absence of bioturbation, *Clostridium* spore counts in cap material remained below detection limits (<5 spores/g dry sediment) following 40 days of incubation. However, in the presence of *Nereis*, *Clostridium* was detected throughout the length of cap material, generally decreasing in concentration from the cap/dredged material interface to the surface. Microbial spores are the same size as very fine clay particles and should behave similarly (Bitton and Marshall 1980). Therefore, it is expected that movement of contaminated sediment through a breached cap is a function of depth, decreasing as the cap depth increases.

55. Movement of soluble contaminants through intact burrows is not a straightforward diffusion problem. Davis (1980) demonstrated that the burrow

wall of *Nephtys* absorbed soluble copper as a function of copper concentration and sediment wall organic content. This sorptive capacity may reduce contaminant transfer through a cap, even when it is breached.

56. In the presence of bioturbation, a 5-cm cap of any material tested was unable to seal the Black Rock sediments from biota and the overlying water. However, the presence of a 5-cm cap with polychaetes served to reduce water column spore counts and contaminant uptake by clams and polychaetes to levels below that observed with uncapped dredged material. This is especially evident in the New Haven cap experiment when the uncapped Black Rock treatment was conducted.

57. In the absence of bioturbation, a 5-cm cap appeared to be generally effective in preventing the movement of contaminants into the overlying water and biota. This is in agreement with the results of Rubinstein, Gillian, and Gregory (1984), who showed that simply isolating organisms (fish) from contact with contaminated sediment with a 1-mm mesh screen significantly reduced PCB body burdens compared to organisms allowed to contact the sediment. Physical isolation of contaminated sediment through capping therefore appears to be a viable means of effectively reducing contaminant bioaccumulation by water column organisms.

Thickness and Relative Effectiveness of Cap Material

58. As pointed out earlier in the results section, varying initial contaminant concentrations in the clams and polychaetes made comparison of bioaccumulation results between experiments using different cap materials difficult. However, all 50-cm caps were effective in isolating the Black Rock sediment in the presence of bioturbation while none of the 5-cm caps were totally effective in the presence of bioturbation. This points to the need to isolate the contaminated dredged material from benthic organism activity.

59. Results of the small reactor unit experiments demonstrated that cap depths as shallow as 2 cm can exert considerable influence on sediment-water interactions. A 2-cm cap resulted in a 40- to 81-percent reduction in overlying water oxygen demand and transfer of NH_4^+-N from Black Rock sediment into the overlying water. A cap depth of 22 cm of any material (sand, silt, or New Haven sediment) was sufficient to stop chemical exchanges between capped Black Rock sediment and the overlying water.

60. The efficiency of cap material in preventing overlying water DO depletion and NH_4^+-N release attributable to the Black Rock sediment was in the order: New Haven sediment > Vicksburg silt > sand. A minimum thickness of 10 cm of New Haven sediment was required to stop NH_4^+-N releases. Such results were in relatively close agreement with PCB and PAH bioaccumulation results for *Rangia* in the 5-cm + polychaete treatment. A 5-cm New Haven sediment or Vicksburg silt cap was relatively more effective than a 5-cm sand cap in preventing the movement of PCB and PAH compounds into *Rangia* in the water column. Chemical and biological uptake data results therefore indicate that cap materials with higher proportions of clay and silt are more effective in preventing the movement of contaminants into the overlying water and biota than sand. This enhanced effectiveness relative to sand may be due to greater adsorptive capacity for contaminants by clays and silt compared to sand. However, a thick cap of any of the materials tested can effectively isolate dredged material from the overlying water.

61. The small reactor unit capping experiment conducted with Black Rock sediment whose solids content had been lowered demonstrated the importance of engineering considerations in capping operations. Capping with sand sealed the Black Rock sediment with 54-percent solids from the overlying water. Lowering the solids content of the Black Rock sediment to 30 percent, however, allowed dredged material to mingle freely with the sand and prevent formation of an effective cap. The engineering properties of a dredged material and a proposed cap material should therefore be closely examined prior to capping to determine their compatibility. There may also have to be a trade-off between the effectiveness of the cap and its persistence in the aquatic environment. Morton and Miller (1980) reported that a sand cap was found to be physically more stable than a silt cap, trends apparently opposite to those reported here for cap effectiveness.

PART V: SUMMARY AND CONCLUSIONS

62. Analyses of DO and NH_4^+-N in the overlying water in the small reactor units revealed that increasing cap depths prevented the transfer of dissolved constituents to the overlying water. The efficiency of cap materials in preventing DO depletion and NH_4^+-N releases into the overlying water attributable to the capped dredged material was in the order: New Haven sediment clay > Vicksburg silt > sand. These chemical results were in relatively close agreement with PCB and PAH bioaccumulation results for *Rangia* in the 5-cm + polychaete treatments in the large reaction chambers. A 5-cm New Haven sediment or Vicksburg silt cap was relatively more effective than a 5-cm sand cap in preventing the movement of PCB and PAH compounds into *Rangia*. Cap materials with higher proportions of clay and silt should, therefore, be more effective than cap materials consisting predominately of sand in preventing contaminant movement into the overlying water and biota. However, a thick cap (50 cm or more) of any of the cap materials tested effectively isolated the overlying water and nonburrowing biota from the dredged material. A depth of 22 cm of any cap material was sufficient to stop chemical exchanges between Black Rock sediment and the overlying water in the absence of bioturbation. However, capping of diluted Black Rock sediment having a lower solids content with 30 cm of sand did not stop sediment-water interactions. This finding emphasizes that sound engineering judgments on the stability of sediments and cap material and dredging methods must be made prior to capping. Of equal important is the need to ensure that the proper cap depth is achieved during the actual cap placement operation and that cap integrity is maintained afterwards.

63. Chemical analysis of polychaete tissue and visual observation showed that *Nereis* penetrated both the 5-cm and 50-cm caps, resulting in a high level of bioturbation. However, even under these bioturbation conditions [100 large (>300 mm) polychaetes per square metre], neither *Rangia* body burdens nor water column concentrations of PCBs, PAHs, or heavy metals showed a significant increase compared to cap material alone in experimental units with a 50-cm cap. At the end of 10 and 40 days of exposure, however, *Rangia* in experimental units with a 5-cm cap with polychaetes showed significantly increased PCB and PAH body burdens compared to *Rangia* in the cap material control treatments. These results indicate that a 50-cm cap of any of the types

tested, even when penetrated by organisms, is effective in preventing the transfer of chemical constituents and microbial spores to the overlying water and biota during a 40-day experiment.

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Table 1

Experimental Design for Black Rock Sediment With Various Caps

Treatment	Animals in Reactor Unit	
	Polychaetes	Suspended Clams
Control (various cap materials)	X	X
5-cm cap	X	X
5-cm cap		X
50-cm cap	X	X
50-cm cap		X
Black Rock	X	X

Table 2

Polyaromatic Hydrocarbon Compounds Determined in Water and Tissue Samples

Two Ring Compounds	Three Ring Compounds
Naphthalene	Fluorene
Benzothiophene	Dibenzothiophene
2-Methylnaphthalene	Phenanthrene
1-Methylnaphthalene	Anthracene
Biphenyl	1-Methylphenanthrene
2,6-Dimethylnaphthalene	Fluoranthene
2,3,6-Trimethylnaphthalene	
Four Ring Compounds	**Five Ring Compounds**
Pyrene	Benzo (e) Pyrene
Chrysene	Benzo (a) Pyrene
	Perylene

Table 3

Heavy Metal Concentrations and Selected Sediment Physical Characteristics

Sediment	Metal Concentration µg/g Dry Weight Cd	Cu	Pb	Zn	Hg	TOC, %	Texture, percent Sand:Silt:Clay
Sand	0.08	0.24	0.63	5.8	<0.1	0.0	100:0:0
Vicksburg silt	0.16	23	7.9	39.3	<0.1	1.1	0:81.2:18.8
New Haven	2.92	202	94.5	273	0.97	3.1	0:58.5:41.5
Black Rock	20.5	2525	368	1412	3.34	8.2	28.7:46.3:25.0

Table 4

Sediment PAH Concentrations

Parameter	Concentration at Indicated Sediment µg/g Dry Weight Sand	Vicksburg Silt	New Haven	Black Rock
Naphthalene	ND*	ND	0.01	4.05
Benzothiophene	ND	ND	0.003	1.16
2-Methylnaphthalene	ND	ND	0.006	6.39
1-Methylnaphthalene	ND	ND	0.001	6.07
Biphenyl	ND	ND	0.005	1.36
2.6-Dimethylnaphthalene	ND	ND	ND	2.14
2,3-6-Trimethylnaphthalene	ND	ND	0.008	3.72
Fluorene	ND	ND	0.010	6.77
Dibenzothiophene	ND	ND	0.302	37.83
Phenanthrene	ND	ND	0.040	27.83
Anthracene	ND	ND	0.017	11.22
1-Methylphenanthrene	ND	ND	0.021	18.69
Fluoranthene	ND	ND	0.140	48.26
Pyrene	ND	ND	0.095	31.78
Chrysene	ND	ND	0.093	49.18
Benzo (e) Pyrene	ND	ND	0.064	8.61
Benzo (a) Pyrene	ND	ND	0.135	38.32
Perylene	ND	ND	0.053	11.17
Total	ND	ND	1.01	314.55

* ND = not detected (detection limit = 0.5 ng/g).

Table 5

Sediment PCB Concentrations*

Isomer Group	Concentration at Indicated Sediment µg/g Dry Weight			
	Sand	Vicksburg Silt	New Haven	Black Rock
Total monochlorobiphenyls	<0.5	<0.05	<0.5	<0.5
Total dichlorobiphenyls	0.05	<0.01	0.73	1.9
Total trichlorobiphenyls	0.06	<0.01	0.04	1.4
Total tetrachlorobiphenyls	<0.01	<0.01	0.17	3.4
Total pentachlorobiphenyls	<0.01	<0.01	0.02	3.3
Total hexachlorobiphenyls	<0.01	<0.01	0.06	7.1
Total heptachlorobiphenyls	<0.01	<0.01	<0.01	0.19
Total octachlorobiphenyls	<0.01	<0.01	<0.01	0.24
Total nonachlorobiphenyls	<0.01	<0.01	<0.01	0.08
Total decachlorobiphenyls	<0.01	<0.01	<0.01	0.02
Total PCBs	0.11	<0.01	1.02	17.63

* Detection limits = <0.5 µg/g for total monochlorobiphenyls and <0.01 µg/g for all other PCB isomer groups.

Table 6

Water Column Metal Concentrations Following 40 days of Incubation*

Treatment	Concentration in Indicated Metal, µg/ℓ ± SE				
	Cd	Cu	Pb	Zn	Hg
		Sand Cap			
Sand control	3.8 ± 0.4	4 ± 0	85 ± 22	<50	0.7 ± 0.4
5-cm cap	6.5 ± 1.2	9 ± 2	70 ± 27	<50	1.0 ± 0.6
5-cm cap + polychaetes	4.9 ±0.2	20 ± 4	91 ± 41	<50	0.7 ± 0.3
50-cm cap	5.1 ± 1.0	4 ± 1	72 ± 32	<50	1.5 ± 0.6
50-cm cap + polychaetes	4.4 ± 0.3	6 ± 0.3	54 ± 17	<50	0.3 ± 0.3
Inflow water	6	6	151	<50	1.6
		New Haven Cap			
New Haven control	2 4 ± 1.7	1 ± 1	5 ± 2	<50	<0.001
5-cm cap	3 6 ± 0.6	1	6 ± 2	<50	<0.001
5-cm cap + polychaetes	3.2 ± 2.5	12 ± 5	16 ± 10	<50	<0.001
50-cm cap	4.9 ± 4.9	2 ± 2	8 ± 4	<50	<0.001
50-cm cap + polychaetes	1.8 ± 1.1	<1	6 ± 2	<50	<0.001
Inflow water	<0.1	<1	5	<50	<0.001
		Uncapped Sediment			
Black Rock (with polychaetes)	4.8 ± 3.0	35 ± 24	3 ± 2	72 ± 8	<0.001

* Samples from the Vicksburg silt experiment were lost during shipment.

Table 7

Water Column PCB Concentrations Following 40 Days of Incubation

Treatment	Concentration in Indicated PCB Isomer Group (Number of Chlorine Atoms per Group), µg/L ± SE								Total PCB
	1	2	3	4	5	6	7	8	
Sand Cap									
Sand control	<0.5	0.58 ± 0.10	0.11 ± 0.04	0.02 ± 0.01	0.03 ± 0.02	0.03 ± 0.03	<0.01	<0.01	0.76 ± 0.23
5-cm cap	<0.5	0.49	0.34	0.01	0.04	0.03	0.01	0.02	1.02
5-cm cap + polychaetes	SL	SL	SL	0.07 ± 0.01	SL	SL	SL	SL	SL
50-cm cap	<0.5	0.38 ± 0.04	0.36 ± 0.03*	SL	0.03 ± 0.01	0.04 ± 0.02	<0.01	<0.01	0.90 ± 0.01
50-cm cap + polychaetes	SL	SL	SL	0.04	SL	SL	SL	SL	SL
Inflow water	<0.5	0.77	0.13		0.03	0.04	<0.01	<0.01	1.01
New Haven Cap									
New Haven control	<0.5	2.82 ± 1.75	1.53 ± 0.54	0.92 ± 0.42	0.006 ± 0.007	<0.01	<0.01	<0.01	5.27 ± 1.97
5-cm cap	<0.5	3.89 ± 1.53	1.42 ± 0.90	1.05 ± 0.68	0.003 ± 0.003	<0.01	<0.01	<0.01	4.22 ± 2.17
5-cm cap + polychaetes	<0.5	1.43 ± 0.83	1.31 ± 0.64	0.78 ± 0.48	0.007 ± 0.003	<0.01	<0.01	<0.01	3.99 ± 1.80
50-cm cap	<0.5	1.57 ± 0.46	0.82 ± 0.43	0.55 ± 0.34	0.01 ± 0.01	<0.01	<0.01	<0.01	2.95 ± 0.34
50-cm cap + polychaetes	<0.5	0.95 ± 0.38	0.83 ± 0.43	0.67 ± 0.57	0.02 ± 0	<0.01	<0.01	<0.01	2.47 ± 1.03
Inflow water	<0.5	0.71	1.7	1.3	<0.01	<0.01	<0.01	<0.01	3.71
Vicksburg Silt Cap									
Vicksburg silt control	3.2 ± 1.0	0.02 ± 0.005	0.06 ± 0.03	0.03 ± 0.04	0.01 ± 0.02	0.02 ± 0.03	<0.01	<0.01	3.30 ± 1.07
5-cm cap	1.9 ± 0.40	<0.01	0.07 ± 0.05	<0.01	<0.01	0.01 0.01	<0.01	<0.01	1.98 ± 0.46
5-cm cap + polychaetes	3.5 ± 0.62	0.03 ± 0.02	0.09 ± 0.07	<0.01	<0.01	<0.01	<0.01	<0.01	3.64 ± 0.67
50-cm cap	1.6 ± 0.56	0.02 ± 0.02	0.11 ± 0.04	0.01 ± 0.00	<0.01	0.02 ± 0.01	<0.01	<0.01	1.75 ± 0.54
50-cm cap + polychaetes	2.2 ± 0.30	0.01 ± 0.01	0.06 ± 0.01	0.02 ± 0.04	<0.01	<0.01	<0.01	<0.01	2.33 ± 0.29
Inflow water	1.3	.04	0.15	0.01	<0.01	0.03	<0.01	<0.01	1.53
Upcapped Sediment									
Black Rock (with polychaetes)	<0.5	1.12 ± 0.27	0.65 ± 0.19	1.61 ± 1.20	0.03 ± 0.01	<0.01	<0.01	< 0.01	2.08 ± 0.57

* Significantly ($p < 0.05$) higher than respective cap material control.

Table 8

Water Column PAH Concentrations Following 40 Days of Incubation

Treatment	Concentration in Indicated Sediment, ng/ℓ	
	New Haven Cap	Vicksburg Silt Cap
Control	59	50
5-cm cap	20	35
5-cm cap + polychaetes	19	45
50-cm cap	59	98
50-cm cap + polychaetes	41	112
Inflow water	65	49
Black Rock sediment	10	--

Table 9

Heavy Metal Concentration in *Rangia* Tissue at 10 Days

Treatment	Concentration of Indicated Metal, µg/g ± Standard Error				
	Cd	Cu	Pb	Zn	Hg
			Sand Cap		
Sand control	1.9 ± 0.4	32.7 ± 10.0	18.5 ± 10.1	86.7 ± 14.0	<0.02
5-cm cap	1.1 ± 0.1	28.4 ± 3.8	5.9 ± 3.6	57.8 ± 2.8	<0.02
5-cm cap + polychaetes	2.3 ± 1.1	34.8 ± 5.5	15.9 ± 13.1	179 ± 111	<0.02
50-cm cap	1.3 ± 0.1	32.9 ± 7.0	7.1 ± 3.3	59.3 ± 3.8	<0.02
50-cm cap + polychaetes	0.7 ± 0.2	26.2 ± 3.7	6.5 ± 4.6	67.2 ± 7.1	<0.02
			New Haven Cap		
New Haven control	1.2 ± 0.2	44.1 ± 1.2	4.4 ± 0.6	73.3 ± 10.0	2.04 ± 0.19
5-cm cap	1.5 ± 0.0	49.4 ± 4.2	4.7 ± 0.5	81.1 ± 10.3	1.84 ± 0.18
5-cm cap + polychaetes	1.3 ± 0.1	51.6 ± 6.4	4.7 ± 0.3	70.9 ± 7.4	2.06 ± 0.18
50-cm cap	1.4 ± 0.1	47.2 ± 1.2	9.2 ± 5.1	72.4 ± 6.4	2.37 ± 0.13
50-cm cap + polychaetes	1.2 ± 0.1	45.8 ± 1.3	5.3 ± 0.6	60.7 ± 6.1	2.34 ± 0.14
			Vicksburg Silt Cap		
Vicksburg silt control	1.1 ± 0.1	41.6 ± 3.6	2.1 ± 1.0	62.3 ± 5.2	2.7 ± 0.5
5-cm cap	0.9 ± 0.1	49.2 ± 3.8	2.0 ± 1.2	65.1 ± 3.0	3.3 ± 1.0
5-cm cap + polychaetes	1.0 ± 0.1	48.5 ± 1.7	3.2 ± 0.6	65.2 ± 3.7	3.0 ± 0.1
50-cm cap	0.9 ± 0.1	39.3 ± 3.3	2.6 ± 0.2	58.7 ± 2.0	2.4 ± 0.2
50-cm cap + polychaetes	0.8 ± 0.1	42.6 ± 3.6	1.5 ± 0.6	58.2 ± 3.7	4.3 ± 1.7
			Uncapped Sediment		
Black Rock (with polychaetes)	1.5 ± 0.7	50.2 ± 2.5	5.1 ± 0.7	62.7 ± 3.2	2.28 ± 0.32

Table 10

Heavy Metal Concentration in *Rangia* Tissue at 40 Days

Treatment	Concentration of Indicated Metal, µg/g ± SE				
	Cd	Cu	Pb	Zn	Hg
Sand Cap					
Sand control	1.7 ± 0.2	41.2 ± 4.9	3.8 ± 1.1	124 ± 38	0.0001 ± 0.0000
5-cm cap	1.3 ± 0.3	44.5 ± 6.0	2.1 ± 0.3	82 ± 14	0.0001 ± 0.0000
5-cm cap + polychaetes	2.6 ± 0.8	39.4 ± 4.0	3.8 ± 0.8	77 ± 8	0.0001 ± 0.0000
50-cm cap	1.2 ± 0.2	39.9 ± 6.7	2.0 ± 0.1	65 ± 7	0.0001 ± 0.0000
50-cm cap + polychaetes	2.6 ± 1.8	36.9 ± 1.0	4.5 ± 2.3	132 ± 63	0.0001 ± 0.0000
New Haven Can					
New Haven control	0.9 ± 0.1	20.7 ± 1.9	4.1 ± 0.6	99 ± 31	2.96 ± 0.17
5-cm cap	0.8	33.4	3.7	63	2.10 ± 0.27
5-cm cap + polychaetes	0.9 ± 0.2	26.3 ± 4.2	3.3 ± 0.9	69 ± 7	2.82 ± 0.27
50-cm cap	0.9 ± 0.2	24.5 ± 1.9	2.4 ± 0.5	58 ± 3	3.47 ± 0.27
50-cm cap + polychaetes	0.7 ± 0.1	21.1 ± 2.2	2.1 ± 0.7	59 ± 6	2.54 ± 0.28
Vicksburg Silt Cap					
Vicksburg silt control	1.2 ± 0.1	35.4 ± 1.4	2.6 ± 0.3	62 ± 1	2.93 ± 0.59
5-cm cap	1.2 ± 0.2	46.0 ± 5.3	6.0 ± 1.5	86 ± 15	3.75 ± 0.49
5-cm cap + polychaetes	2.1 ± 0.4	46.3 ± 1.4*	2.8 ± 0.8	66 ± 5	3.93 ± 1.08
50-cm cap	1.9 ± 0.5	43.1 ± 3.6	4.8 ± 1.4	136 ± 67	3.10 ± 0.85
50-cm cap + polychaetes	1.3 ± 0.1	43.6 ± 3.9	4.9 ± 1.0	74 ± 10	4.43 ± 0.30
Uncapped Sediment					
Black Rock (with polychaetes)	2.5 ± 0.9	41.1 ± 7.3	6.8 ± 3.7	174 ± 103	2.19 ± 0.21

* Significantly ($p < 0.05$) higher than respective cap material control.

Table 11

PAH Concentration in *Rangia* Tissue at 10 Days

Treatment	Concentration in Indicated Compound, µg/g Lipid ± SE				
	Two Ring Compounds	Three Ring Compounds	Four Ring Compounds	Five Ring Compounds	Total PAH
		Sand Cap			
Sand control	0.04 ± 0.02	0.29 ± 0.22	0.05 ± 0.05	0.03 ± 0.03	0.42 ± 0.28
5-cm cap	0.02 ± 0.00	0.35 ± 0.21	0.31 ± 0.18	0.02 ± 0.02	0.70 ± 0.38
5-cm cap + polychaetes	0.10 ± 0.05	4.41 ± 2.37	5.04 ± 1.37*	0.54 ± 0.03	9.10 ± 3.90*
50-cm cap	0.01 ± 0.01	0.13 ± 0.06	0.03 ± 0.00	0.03 ± 0.03	0.20 ± 0.05
50-cm cap + polychaetes	0.17 ± 0.15	0.24 ± 0.13	0.35 ± 0.35	<0.001	0.76 ± 0.63
		New Haven Cap			
New Haven control	0.25 ± 0.25	0.04 ± 0.04	0.001	<0.001	0.30 ± 0.20
5-cm cap	0.30 ± 0.20	0.001	1.4 ± 1.4	< 0.001	1.70 ± 1.30
5-cm cap + polychaetes	2.20 ± 2.10	58.7 ± 19.5*	48.1 ± 18.2*	4.30 ± 1.30*	113 ± 40.3*
50-cm cap	0.60 ± 0.30	<0.001	< 0.001	<0.001	0.60 ± 0.30
50-cm cap + polychaetes	0.06 ± 0.06	<0.001	<0.001	<0.001	0.06 ± 0.06
		Vicksburg Silt Cap			
Vicksburg silt control	<0.001	0.30 ± 0.27	<0.001	<0.001	0.30 ± 0.27
5-cm cap	<0.001	<0.001	<0.001	<0.001	<0.001
5-cm cap + polychaetes	1.76 ± 1.76	44.1 ± 16.8*	20.0 ± 4.05*	0.1 ± 0.1	69.3 ± 23.2*
50-cm cap	0.71 ± 0.46	0.62 ± 0.38	<0.001	<0.001	1.32 ± 0.67
50-cm cap + polychaetes	0.40 ± 0.23	<0.001	<0.001	<0.001	0.40 ± 0.23
		Uncapped Sediment			
Black Rock (with polychaetes)	0.70 ± 0.70	71.5 ± 23.1	49.2 ± 11.8	3.5 ± 1.8	124.9 ± 36.1

* Significantly ($p < 0.05$) higher than respective cap material control.

Table 12

PAH Concentration in *Rangia* Tissue at 40 Days

Treatment	Concentration in Indicated Compound, µg/g Lipid ± SE				
	Two Ring Compounds	Three Ring Compounds	Four Ring Compounds	Five Ring Compounds	Total PAH
		Sand Cap			
Sand control	0.74 ± 0.15	4.36 ± 2.20	1.22 ± 1.22	0.34 ± 0.34	6.67 ± 3.90
5-cm cap	0.72 ± 0.34	2.90 ± 1.11	2.05 ± 1.07	<0.001	5.67 ± 2.38
5-cm cap + polychaetes	0.78 ± 0.33	66.4 ± 47.0	49.2 ± 31.2	19.1 ± 9.69	135.0 ± 84.5
50-cm cap	0.54 ± 0.23	14.2 ± 12.9	18.1 ± 18.1	6.31 ± 6.31	39.1 ± 37.2
50-cm cap + polychaetes	0.69 ± 0.20	1.77 ± 1.07	0.19 ± 0.19	<0.001	2.64 ± 1.38
		New Haven Cap			
New Haven control	0.49 ± 0.25	<0.001	<0.001	<0.001	0.50 ± 0.30
5-cm cap	0.44 ± 0.42	0.32 ± 0.33	2.60 ± 2.60	<0.001	3.30 ± 3.30
5-cm cap + polychaetes	0.50 ± 0.50	14.4 ± 4.20*	14.4 ± 1.80*	4.50 ± 0.60*	33.4 ± 6.20*
50-cm cap	0.55 ± 0.46	<0.001	<0.001	<0.001	0.55 ± 0.50
50-cm cap + polychaetes	0.63 ± 0.32	<0.001	<0.001	<0.001	0.63 ± 0.30
		Vicksburg Silt Cap			
Vicksburg Silt control	<0.001	<0.001	<0.001	<0.001	<0.001
5-cm cap	<0.001	<0.001	<0.001	<0.001	<0.001
5-cm cap + polychaetes	0.68 ± 0.60	18.6 ± 6.15*	16.7 ± 4.36*	5.62 ± 2.8[illegible]	41.1 ± 13.4*
50-cm cap	0.62 ± 0.62	0.19 ± 0.11	<0.001	<0.001	0.81 ± 0.71
50-cm cap + polychaetes	0.10 ± 0.10	0.01 ± 0.01	<0.001	<0.001	0.10 ± 0.09
		Uncapped Sediment			
Black Rock (with polychaetes)	0.01 ± 0.01	44.2 ± 6.60	57.0 ± 4.70	14.3 ± 0.45	116 ± 11.8

* Significantly ($p < 0.05$) higher than respective cap material control.

Table 13

PCB Concentration in *Rangia* Tissue at 10 Days

Treatment	Concentration in Indicated PCB Isomer Group (Number of Chlorine Atoms per Group) µg/g Lipid ± SE								Total PCB
	1	2	3	4	5	6	7	8	
Sand Cap									
Sand control	<0.5	18.2 ± 2.47	6.62 ± 0.53	8.31 ± 0.41	4.66 ± 0.70	0.68 ± 0.68	<0.01	2.37 ± 1.22	40.9 ± 0.84
5-cm cap	<0.5	17.7 ± 5.59	4.87 ± 1.02	5.47 ± 0.53	4.87 ± 1.02	3.25 ± 0.68*	<0.01	2.04 ± 1.67	38.1 ± 10.5
5-cm cap + polychaetes	<0.5	20.4 ± 3.33	7.98 ± 1.47	19.5 ± 2.53*	13.8 ± 1.49	25.3 ± 6.79*	<0.01	1.47 ± 1.47	88.4 ± 11.5
50-cm cap	<0.5	21.1 ± 3.23	6.31 ± 0.69	6.70 ± 1.92	7.28 ± 2.50	2.34 ± 2.34	<0.01	3.77 ± 1.01	47.5 ± 7.79
50-cm cap + polychaetes	<0.5	12.6 ± 1.56	4.81 ± 0.36	6.17 ± 1.41	7.11 ± 3.35	3.19 ± 1.77	<0.01	1.72 ± 1.00	35.6 ± 5.67
New Haven Cap									
New Haven control	<0.5	8.28 ± 0.81	3.73 ± 1.23	2.73 ± 0.46	<0.01	1.62 ± 0.88	<0.01	< .01	15.3 ± 1.46
5-cm cap	<0.5	9.21 ± 1.50	2.64 ± 0.27	3.38 ± 0.56	3.38 ± 0.56*	1.67 ± 1.40	<0.01	< .01	20.9 ± 3.19
5-cm cap + polychaetes	<0.5	7.18 ± 1.05	3.77 ± 1.06	9.34 ± 1.24*	8.19 ± 2.78*	14.42 ± 3.60*	<0.01	< .01	83.4 ± 49.5
50-cm cap	<0.5	7.66 ± 2.86	1.48 ± 0.74	2.87 ± 0.74	0.76 ± 0.76	2.15 ± 0.79	<0.01	<0.01	14.9 ± 1.83
50-cm cap + polychaetes	<0.5	6.92 ± 0.67	2.56 ± 0.48	3.32 ± 1.24	3.32 ± 1.24	6.35 ± 4.28	<0.01	<0.01	145 ± 130.9
Vicksburg Silt Cap									
Vicksburg silt control	<0.5	0.56 ± 0.56	<0.01	<0.01	0.56 ± 0.56	<0.01	<0.01	<0.01	1.13 ± 1.13
5-cm cap	<0.5	<0.01	<0.01	1.85 ± 1.30	<0.01	<0.01	<0.01	<0.01	1.85 ± 1.30
5-cm cap + polychaetes	<0.5	1.01 ± 1.01	2.12 ± 1.06	6.73 ± 1.34*	6.73 ± 1.34*	8.59 ± 0.99*	<0.01	<0.01	24.1 ± 5.14*
50-cm cap	<0.5	<0.01	1.04 ± 1.04	1.94 ± 0.98	2.85 ± 1.37	<0.01	<0.01	<0.01	5.83 ± 2.94
50-cm cap + polychaetes	<0.5	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Uncapped Sediment									
Black Rock (with polychaetes)	<0.5	5.65 ± 1.66	5.42 ± 1.20	10.99 ± 1.94	12.92 ± 2.90	20.65 ± 5.02	<0.01	<0.01	55.41 ± 11.75

* Significantly ($p < 0.05$) higher than respective cap material control.

Table 14

PCB Concentration in *Rangia* Tissue at 40 Days

Treatment	Concentration in Indicated PCB Isomer Group (Number of Chlorine Atoms per Group) µg/g Lipid ± SE								Total PCB
	1	2	3	4	5	6	7	8	
Sand Cap									
Sand control	<0.5	4.17 ± 4.17	10.5 ± 1.61	2.98 ± 1.50	<0.01	<0.01	<0.01	<0.01	17.6 ± 3.68
5-cm cap	<0.5	46.2 ± 37.6	15.0 ± 1.68	6.58 ± 1.57	6.07 ± 6.07	<0.01	<0.01	<0.01	74.5 ± 45.6
5-cm cap + polychaetes	<0.5	30.0 ± 19.9	17.8 ± 3.90	10.7 ± 6.04	13.0 ± 8.11	25.8 ± 13.3	<0.01	<0.01	97.3 ± 36.8*
50-cm cap	<0.5	37.0 ± 27.6	7.81 ± 0.76	2.83 ± 1.53	6.73 ± 3.37	2.83 ± 1.53	<0.01	<0.01	57.2 ± 32.2
50-cm cap + polychaetes	<0.5	10.4 ± 5.40	16.7 ± 0.75	2.15 ± 2.15	<0.01	<0.01	<0.01	<0.01	29.2 ± 6.71
New Haven Cap									
New Haven control	<0.5	15.28 ± 1.20	1.89 ± 0.99	2.96 ± 0.32	1.87 ± 0.87	4.81 ± 0.91	<0.01	<0.01	26.80 ± 0.61
5-cm cap	<0.5	28.35 ± 4.03	2.53 ± 0.38	3.57 ± 1.36	3.57 ± 1.36	5.65 ± 3.44	<0.01	<0.01	43.66 ± 5.47
5-cm cap + polychaetes	<0.5	10.79 ± 1.05	3.85 ± 0.41	11.11 ± 1.21*	17.38 ± 1.10*	32.67 ± 1.86*	<0.01	<0.01	75.80 ± 4.28*
50-cm cap	<0.5	32.83 ± 4.54	2.40 ± 0.02	4.01 ± 0.82	1.61 ± 0.80	2.40 ± 0.02	<0.01	<0.01	43.25 ± 6.17
50-cm cap + polychaetes	<0.5	15.97 ± 2.84	2.52 ± 0.19	2.52 ± 0.19	1.61 ± 0.82	4.13 ± 0.78	<0.01	<0.01	26.74 ± 1.84
Vicksburg Silt Cap									
Vicksburg silt control	<0.5	<0.01	<0.01	2.08 ± 2.08	<0.01	<0.01	<0.01	<0.01	2.08 ± 2.08
5-cm cap	<0.5	3.45 ± 0.53*	0.58 ± 0.59	2.62 ± 1.33	0.58 ± 0.58	1.17 ± 1.17	<0.01	<0.01	8.53 ± 3.44
5-cm cap + polychaetes	<0.5	3.30 ± 0.24*	2.34 ± 1.18*	8.94 ± 1.65*	11.37 ± 1.44*	18.84 ± 2.36*	<0.01	<0.01	45.04 ± 6.89*
50-cm cap	<0.5	0.58 ± 0.59	<0.01	4.44 ± 4.44	<0.01	<0.01	<0.01	<0.01	5.03 ± 4.18
50-cm cap + polychaetes	<0.5	0.69 ± 0.69	<0.01	3.26 ± 2.30	<0.01	<0.01	<0.01	<0.01	3.95 ± 2.22
Uncapped Sediment									
Black Rock (with polychaetes)	<0.5	11.12 ± 1.12	5.56 ± 0.56	18.34 ± 0.87	28.35 ± 0.92	57.54 ± 1.97	<0.01	1.67 ± 0.84	122.57 ± 4.45

* Significantly ($p < 0.05$) higher than respective cap material control.

Table 15

Heavy Metal Concentrations in *Nereis* Tissue Following 40 Days of Exposure

Treatment	Concentration of Indicated Metal, µg/g Dry Weight ± SE				
	Cd	Cu	Pb	Zn	Hg
		Sand Cap			
Sand control	0.4 ± 0.1	31.2 ± 11.0	3.7 ± 1.6	105 ± 9	<0.02
5-cm cap + polychaetes	1.0 ± 0.1*	142 ± 23*	4.9 ± 1.0	136 ± 25	<0.02
50-cm cap + polychaetes	1.0 ± 0.1*	21.3 ± 1.9	2.2 ± 0.3	97 ± 11.2	<0.02
		New Haven Cap			
New Haven control	0.3 ± 0.1	20.7 ± 5.2	3.2 ± 1.7	111 ± 7	<0.02
5-cm cap + polychaetes	0.4 ± 0.2	74.2 ± 38.7	2.2 ± 0.2	130 ± 6	<0.02
50-cm cap + polychaetes	0.3 ± 0.1	18.8 ± 0.7	2.6 ± 0.1	116 ± 12	<0.02
		Vicksburg Silt Cap			
Vicksburg silt control	0.7 ± 0.3	19.2 ± 0.3	7.8 ± 5.9	76 ± 14	<0.02
5-cm cap + polychaetes	0.9 ± 0.1	84.2 ± 5.5*	5.4 ± 1.3	109 ± 8	<0.02
50-cm cap + polychaetes	0.6 ± 0.0	18.8 ± 0.5	6.3 ± 0.6	84 ± 5	<0.02
		Uncapped Sediment			
Black Rock (with polychaetes)	1.3 ± 0.4	146 ± 43	1.4 ± 0.2	171 ± 28	<0.02

* Significantly ($p < 0.05$) higher than respective cap material control.

Table 16

PAH Concentration in *Nereis* Tissue at 40 Days

Treatment	Concentration of Indicated Compound, µg/g Lipid ± SE				
	Two Ring Compounds	Three Ring Compounds	Four Ring Compounds	Five Ring Compounds	Total PAH
		Sand Cap			
Sand control	1.59 ± 0.20	1.74 ± 0.38	0.24 ± 0.24	12.1 ± 10.4	15.7 ± 8.78
5-cm cap + polychaetes	34.0 ± 19.1	105 ± 71.1	38.3 ± 23.3	26.8 ± 13.9	188.0 ± 120.0
50-cm cap + polychaetes	2.09 ± 1.05	0.66 ± 0.34	0.19 ± 0.19	7.96 ± 3.88	10.9 ± 1.88
		New Haven Cap			
New Haven control	8.60 ± 6.00	2.40 ± 0.70	11.3 ± 5.00	1.20 ± 1.20	16.1 ± 5.80
5-cm cap + polychaetes	26.9 ± 14.2	58.7 ± 30.7	41.5 ± 22.9	5.00 ± 2.70	132 ± 63.8
50-cm cap + polychaetes	17.2 13.4	40.6 ± 35.5	28.0 ± 5.20	3.20 ± 1.40	89.0 ± 55.5
		Vicksburg Silt Cap			
Vicksburg silt control	0.55 ± 0.35	0.53 ± 0.53	<0.001	<0.001	1.08 ± 0.59
5-cm cap + polychaetes	8.46 ± 0.80*	40.3 7.07*	10.4 ± 0.97*	6.69 ± 4.36*	68.9 ± 11.8*
50-cm cap + polychaetes	0.59 ± 0.22	3.35 ± 1.64	<0.001	<0.001	3.94 ± 3.03
		Uncapped Sediment			
Black Rock (with polychaetes)	18.7 ± 4.00	50.8 ± 9.60	36.9 ± 12.2	4.10 ± 0.07	110.4 ± 23.4

* Significantly ($p < 0.05$) higher than respective cap material control.

Table 17

PCB Concentration in *Nereis* Tissue at 40 Days

Treatment	Concentration of Indicated PCB Isomer Group (Number of Chlorine Atoms per Group), µg/g Lipid ± SE								
	1	2	3	4	5	6	7	8	PCB
Sand Cap									
Sand control	<0.5	17.5 ± 8.70	7.97 ± 3.17	9.35 ± 3.55	7.49 ± 0.88	<0.01	<0.01	<0.01	42.4 ± 15.7
5-cm cap + polychaetes	<0.5	16.7 ± 4.59	7.82 ± 3.23	7.10 ± 3.87	12.7 ± 5.86	29.8 ± 14.0*	<0.01	<0.01	77.4 ± 32.8
50-cm cap + polychaetes	<0.5	22.1 ± 0.90	8.30 ± 0.71	13.3 ± 0.32	4.79 ± 3.79	<0.01	<0.01	<0.01	47.5 ± 2.50
New Haven Cap									
New Haven control	<0.5	10.12 ± 0.86	0.53 ± 0.27	1.57 ± 0.50	2.39 ± 0.89	<0.01	<0.01	0.74 ± 0.42	21.2 ± 4.01
5-cm cap + polychaetes	<0.5	9.04 ± 1.92	3.02 ± 1.16	9.49 ± 4.04	15.3 ± 6.84	1.05 ± 0.22*	1.05 ± 0.22*	1.05 ± 0.22	71.5 ± 29.28
50-cm cap + polychaetes	<0.5	5.42 ± 0.04	1.75 ± 0.98	4.79 ± 2.50	7.52 ± 5.23	0.84 ± 0.07*	0.84 ± 0.07*	0.84 ± 0.07	41.2 ± 24.33
Vicksburg Silt Cap									
Vicksburg silt control	<0.5	1.33 ± 0.31	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	1.33 ± 0.31
5-cm cap + polychaetes	<0.5	2.40 ± 0.61	1.17 ± 0.65	5.70 ± 1.12*	9.3 ± 4.86*	<0.01	<0.01	<0.01	44.64 ± 8.53*
50-cm cap + polychaetes	<0.5	0.38 ± 0.38	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.38 ± 0.38
Uncapped Sediment									
Black Rock (with polychaetes)	<0.5	7.23 ± 0.94	7.23 ± 0.94	12.86 ± 2.99	28.55 ± 2.78	1.35 ± 0.14	1.35 ± 9.40	1.35 ± 0.14	134.75 ± 15.09

Table 18

Mean Water Column *C. perfringens* Spore Counts for the Black Rock Capping Study

Treatment	Spore Count at Indicated Day of Experiment, Spores/100 ml Water ± SE					
	2	6	15	23	30	31
			Sand Cap			
Sand control	ND	<1	<1	ND	<1	ND
5-cm cap	ND	94 ± 91	2 ± 0.6	5 ± 1.4	<1	ND
5-cm cap + polychaetes	135	250 ± 19*	83 ± 28*	120 ± 10	355 ± 87*	310 ± 107
50-cm cap	ND	<1	<1	1 ± 0.3	7.0 ± 11	<1
50-cm cap + polychaetes	<1	<1	<1	<1	1 ± 0.7	ND
	2	14	24	34	41	
			New Haven Cap			
New Haven control	95 ± 8.6	100 ± 17	85 ± 9.0	30 ± 9.0	23 ± 7.2	
5-cm cap	18 ± 7.7	18 ± 18	40 ± 34	9.0 ± 7.5	16 ± 12	
5-cm cap + polychaetes	1740 ± 997*	725 ± 153*	495 ± 117*	315 ± 128	300 ± 154	
50-cm cap	16 ± 13	4.0 ± 2.4	9.0 ± 1.9	7.0 ± 0.7	7.0 ± 22	
50-cm cap + polychaetes	135 ± 8.8	60 ± 22	40 ± 22	35 ± 16	20 ± 11	
	1	6	14	22	33	40
			Vicksburg Silt Cap			
Vicksburg silt control	<1	<1	<1	<1	<1	<1
5-cm cap	<1	<1	<1	<1	<1	<1
5-cm cap + polychaetes	165 ± 29*	280 ± 84*	60 ± 9.0*	65 ± 27*	75 19*	115 ± 26*
50-cm cap	<1	<1	<1	<1	<1	<1
50-cm cap + polychaetes	<1	<1	<1	<1	<1	<1
	2	14	24	34	41	
			Uncapped Sediment			
Black Rock (with polychaetes)	1660 149	1240 ± 227	840 ± 34	425 ± 38	365 ± 96	

ND = not determined.

* Significantly ($p > 0.05$) higher than respective control.

APPENDIX A: TISSUE AND WATER RESULTS

Table A1

Percent Lipids in *Rangia* and *Nereis* Tissue

Treatment	Percent Lipids in Indicated Organism Wet Weight ± Standard Error		
	Rangia		*Nereis*
	10 Days	40 Days	40 Days
	Sand Cap		
Sand cap control	0.37 ± 0.07	0.22 ± 0.01	1.14 ± 0.27
5-cm cap	0.68 ± 0.10	0 26 ± 0.04	
5-cm cap + polychaetes	0.46 ± 0.11	0.23 ± 0.10	0.76 ± 0.16
50-cm cap	0.54 ± 0.05	0.30 ± 0.05	
50-cm cap + polychaetes	0.55 ± 0.03	0.20 ± 0.06	0.83 ± 0.17
	New Haven Cap		
New Haven control	0.39 ± 0.08	0.35 ± 0.04	1.06 ± 0.19
5-cm cap	0.39 ± 0.04	0.42 ± 0.07	
5-cm cap + polychaetes	0.42 ± 0.05	0.42 ± 0.05	1.03 ± 0.21
50-cm cap	0.47 ± 0.02	0.42 ± 0.00	
50-cm cap + polychaetes	0.57 ± 0.09	0.40 ± 0.03	1.20 ± 0.10
	Vicksburg Silt Cap		
Vicksburg silt control	0.36 ± 0.13	0.35 ± 0.04	0.86 ± 0.18
5-cm cap	0.41 ± 0.21	0.48 ± 0.05	
5-cm cap + polychaetes	0.36 ± 0.05	0.40 ± 0.07	0.69 ± 0.15
50-cm cap	0.34 ± 0.01	0.37 ± 0.12	
50-cm cap + polychaete	0.22 ± 0.04	0.42 ± 0.08	0.69 ± 0.17
	Uncapped Dredged Material		
Black Rock (with polychaetes)	0.43 ± 0.08	0.37 ± 0.03	1.21 ± 0.15

Table A2

Contaminant Concentrations in *Rangia* at Time Zero

Parameter	Sand Cap	New Haven Cap	Vicksburg Silt Cap
Cd, µg/g dry weight	2.77 ± 0.82*	1.21 ± 0.17	1.55 ± 0.14
Cu, µg/g dry weight	42.7 ± 5.51	31.8 ± 0.76	53.1 ± 6.34
Pb, µg/g dry weight	34.5 ± 3.79	3.20 ± 0.14	13.3 ± 2.33
Zn, µg/g dry weight	162 ± 40.5	67.2 ± 5.99	95.8 ± 13.6
Hg, µg/g dry weight	<0.02	1.68 ± 0.06	2.66 ± 0.47
Total PCB, µg/g dry lipid	57.5 ± 2.38	7.08 ± 2.97	5.67 ± 1.96
Total PAH, µg/g dry lipid	32.0 ± 3.01	0.36 ± 0.24	2.17 ± 0.67

* ± standard error.

Table A3

Contaminant Concentrations in *Nereis* at Time Zero

Parameter	Sand Cap	New Haven Cap	Vicksburg Silt Cap
Cd, µg/g dry weight	0.43 ± 0.06*	0.75 ± 0.24	0.91 ± 0.26
Cu, µg/g dry weight	11.3 ± 0.70	19.5 ± 0.44	20.9 ± 0.25
Pb, µg/g dry weight	1.53 ± 0.25	3.04 ± 0.08	12.7 ± 5.03
Zn, µg/g dry weight	98.1 ± 19.3	91.6 ± 5.10	111 ± 17.8
Hg, µg/g dry weight	<0.02	<0.02	0.39 ± 0.08
Total PCB, µg/g dry lipid	9.32 ± 0.95	3.89 ± 2.60	9.06 ± 7.63
Total PAH, µg/g dry lipid	3.33 ± 0.99	0.83 ± 0.69	<0.001

* ± standard error.

Table A4

Overlying Water Oxygen Demand as a Function of Cap Depth and Cap Material

Cap Depth, cm	Oxygen Demand in Indicated Cap Material mg/m²/day ± Standard Deviations			
	Sand	New Haven	Vicksburg Silt	Sand Over Diluted Black Rock
0	-904 ± 32	-904 ± 32	-904 ± 32	-261 ± 3
2	-585 ± 42	-408 ± 13	-372 ± 16	
4	-553 ± 61	ND*	ND	
6	-443 ± 51	ND	ND	
8	-422 ± 48	ND	ND	-263 ± 4
10	-410 ± 40	-423 ± 17	-300 ± 10	
12	-359 ± 11	ND	ND	
14	-222 ± 47	[illegible]	ND	-250 ± 11
18	-259 ± 14	-416 ± 11	-248 ± 3	
22	-116 ± 12	ND	ND	-165 ± 5
26	-128 ± 12	-406 ± 9	-283 ± 22	
30	ND	ND	ND	-171 ± 1
Cap material alone	-115 ± 2	-417 ± 17	-246 ± 41	-115 ± 2

* ND = not determined.

Table A5

Ammonium-Nitrogen Release to the Overlying Water as a Function of Cap Depth and Cap Material

Cap Depth, cm	Release at Indicated Cap Material mg/m²/day ± Standard Deviations			
	Sand	New Haven	Vicksburg Silt	Sand Over Diluted Black Rock
0	312 ± 39	312 ± 39	312 ± 39	222 ± 56
2	182 ± 20	259 ± 2	128 ± 13	163 ± 26
4	137 ± 11	ND*	ND	ND
6	115 ± 11	ND	ND	ND
8	78 ± 2	ND	ND	ND
10	51 ± 8	246 ± 28	76 ± 9	ND
12	27 ± 3	ND	ND	ND
14	22 ± 9	ND	ND	158 ± 16
18	25 ± 8	257 ± 30	18 ± 18	ND
22	9 ± 5	ND	ND	153 ± 14
26	2 ± 1	364 ± 15	10 ± 1	ND
30	ND	ND	ND	82 ± 21
Cap material alone	0	223 ± 3	12 ± 3	0

* ND = not determined.